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THESIS

OPTIMIZING SHIP-TO-SHORE MOVEMENT FOR HOSPITAL SHIP HUMANITARIAN ASSISTANCE OPERATIONS

by

Peter Ward

March 2008

Thesis Advisor:	Javier Salmeron
Second Reader:	Brian Steckler

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The U.S. Navy recently designated Humanitarian Assistance (HA) and Disaster Relief (DR) as core capabilities, recognizing the importance of delivering a potent strategic communications message directly to foreign populations. The Ship-to-Shore Transportation Problem (SSTP) refers to the daily need to determine transportation asset (embarked helicopters, watercraft, and ground vehicles) routing and loading to effect the movement of personnel and patients between Hospital Ship (T-AH) and ashore mission sites during HA/DR operations. The SSTP significantly impacts overall mission performance. The SSTP is formulated as a mixed-integer mathematical optimization model, minimizing cost in a multi-objective merit function reflecting mission performance, personnel strength and transportation asset utilization while reflecting constraints unique to T-AH HA (flight deck limitations, restricted embarkation and debarkation by watercraft). Optimized schedules improve average duration of ashore mission site operations by between 9% and 13% compared to a set of optimistic, pseudo-manually generated schedules, and decrease average time spent by personnel in transit by between 16% and 43%. USNS COMFORT (T-AH 20) treated nearly 95,000 patients in 2007 during an HA deployment; operational efficiencies can translate into thousands more benefiting from HA. This thesis also helps allocate helicopter flight hours, a monthly constraint, over a set of daily SSTP scenarios.

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OPTIMIZING SHIP-TO-SHORE MOVEMENT FOR HOSPITAL SHIP HUMANITARIAN ASSISTANCE OPERATIONS

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

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ABSTRACT

The U.S. Navy recently designated Humanitarian Assistance (HA) and Disaster Relief (DR) as core capabilities, recognizing the importance of delivering a potent strategic communications message directly to foreign populations. The Ship-to-Shore Transportation Problem (SSTP) refers to the daily need to determine transportation asset (embarked helicopters, watercraft, and ground vehicles) routing and loading to effect the movement of personnel and patients between Hospital Ship (T-AH) and ashore mission sites during HA/DR operations. The SSTP significantly impacts overall mission performance. The SSTP is formulated as a mixed-integer mathematical optimization model, minimizing cost in a multi-objective merit function reflecting mission performance, personnel strength and transportation asset utilization while reflecting constraints unique to T-AH HA (flight deck limitations, restricted embarkation and debarkation by watercraft). Optimized schedules improve average duration of ashore mission site operations by between 9% and 13% compared to a set of optimistic, pseudo-manually generated schedules, and decrease average time spent by personnel in transit by between 16% and 43%. USNS COMFORT (T-AH 20) treated nearly 95,000 patients in 2007 during an HA deployment; operational efficiencies can translate into thousands more benefiting from HA. This thesis also helps allocate helicopter flight hours, a monthly constraint, over a set of daily SSTP scenarios.

TABLE OF CONTENTS

I. INTRODUCTION....1
A. UNITED STATES NAVY HUMANITARIAN ASSISTANCE....1
B. NAVAL HUMANITARIAN ASSISTANCE OPTIMIZATION....5
C. HOSPITAL SHIPS AND THE TRANSPORTATION PROBLEM....7
1. Hospital Ship Design and Capabilities....8
2. Previous Hospital Ship Humanitarian Assistance Operations....9
3. Manual Solutions to the Transportation Problem....11
D. THESIS GOALS AND OUTLINE....13

II. MODELING APPROACH....15
A. CHARACTERISTICS OF THE TRANSPORTATION PROBLEM....15
B. SSTP AND THE GENERAL VEHICLE ROUTING PROBLEM....17
C. OBJECTIVE FUNCTION DESCRIPTION....18
1. Degraded Mission Performance from Late Arrival....18
2. Expedite Arrival Penalty and Delay Initial Departure....20
3. Transportation Asset Costs....24
D. MATHEMATICAL FORMULATION....26
1. Sets and Indices....26
2. Parameters (Units)....27
3. Derived Sets and Data (Units for Derived Data Only)....28
4. Decision Variables (Units)....29
5. Mathematical Formulation of T-AH HAT Model....30
6. Description of the Formulation....31
E. IMPLEMENTATION....32

III. COMPUTATIONAL RESULTS AND ANALYSIS....35
A. USER-DEFINED PARAMETERS....35
1. Scenario Parameters....35
2. Nodes....36
3. Topography....37
4. Personnel....37
5. Transportation Assets....38
B. CRITERIA FOR SCHEDULE EVALUATION....39
C. GENERIC OPERATIONAL TOPOGRAPHY SCENARIOS....40
D. APPLICATION OF MONTHLY FLIGHT HOUR CONSTRAINT....42
E. COMPARISON OF MANUAL AND AUTOMATED SCHEDULING....43
1. Generation of Pseudo-Manual Schedules....43
2. Comparison of Individual Pseudo-Manual and Optimized Schedules....44
3. Comparison of Pseudo-Manual and Optimized Schedules....49
F. ANALYSIS OF POTENTIAL T-AH MODIFICATIONS' IMPACT ON MISSION PERFORMANCE....51
1. Analysis: T-AH Certified to Use Two Helicopter Landing Spots....51

2. Analysis: T-AH Modified to Carry Two Patient Tender Watercraft 52
IV. CONCLUSION AND FUTURE RESEARCH 55
A. CONCLUSION 55
B. DEPLOYMENT OF THE OPTIMIZATION TOOL 56
C. DISSEMINATION OF ANALYSIS 56
D. RELATED TOPICS FOR FURTHER RESEARCH 57
LIST OF REFERENCES 59
INITIAL DISTRIBUTION LIST 61

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LIST OF FIGURES

Figure 1. Photograph of USNS COMFORT anchored offshore while conducting HA operations in Haiti during the 2007 deployment....3
Figure 2. Chinese Hospital Ship Commissioned in 2007....4
Figure 3. Marginal *late arrival penalty*.....20
Figure 4. Marginal *expedite arrival penalty*....22
Figure 5. Marginal *delay initial departure*....23
Figure 6. A notional example of the combined potential effect of the two penalties and the incentive described in this section (each shown cumulatively). 24
Figure 7. User-defined scenario parameters....36
Figure 8. User-defined node parameters 36
Figure 9. User-defined topography parameters....37
Figure 10. User-defined personnel parameters....38
Figure 11. User-defined transportation asset parameters 38

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LIST OF TABLES

Table 1. Three generic operational topography scenarios 42
Table 2. Scenario 1 Pseudo-Manual and T-AH HAT Optimized Results Comparison. 45
Table 3. Scenario 2 Pseudo-Manual and T-AH HAT Optimized Results Comparison. 47
Table 4. Scenario 3 Pseudo-Manual and T-AH HAT Optimized Results Comparison. 48
Table 5. Helicopter utilization penalties and the associated quantity of flight hours, for three scenarios, iteratively explored in order to match aggregate flight hours across the scenarios' optimized schedules to the aggregate flight hours derived from the pseudo-manual scheduling process. 50
Table 6. Comparison of (1) pseudo-manual schedules, (2) T-AH HAT optimized schedules without reallocation of helicopter flight hours, and (3) T-AH HAT optimized schedules with flight hour reallocation among three scenarios. 50
Table 7. Comparison of optimized schedules with and without the addition of a second helicopter landing spot. 52
Table 8. Comparison of optimized schedules with and without the addition of patient tender watercraft, over three scenarios. 53

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EXECUTIVE SUMMARY

The U.S. Navy recently designated Humanitarian Assistance (HA) and Disaster Relief (DR) as core capabilities. The value of HA/DR, putting aside obvious moral imperatives, is that it delivers a potent strategic communications message directly to foreign populations.

HA and DR operations, as relatively new competencies for Naval forces, have yet to benefit from the same degree of robust analysis underlying high performance in other core capability areas. The two hospital ships in current inventory, USNS MERCY (T-AH 19) and USNS COMFORT (T-AH 20), have been, and will likely continue to be, centerpiece platforms for Naval HA. The researcher, while participating in a recent HA operation aboard USNS COMFORT, observed and assessed a range of operational problems affecting HA performance. Many of these challenging problems would likely benefit from operations research analysis, particularly mathematical optimization, to help elevate mission performance to a level commensurate with core capability status.

Among these problems, we define the Ship-to-Shore Transportation Problem (SSTP) as the daily need to determine transportation asset (embarked helicopters, watercraft, and ground vehicles) routing and loading to effect the movement of personnel and patients between ship and ashore mission site. The SSTP manifests when the T-AH is not able to moor pier-side, a common occurrence in T-AH HA operations due to the ship's draft and port limitations in developing countries.

Solutions to the SSTP, optimal or otherwise, significantly impact overall mission performance by affecting ashore mission site operation time, itself a critical constraint on the number of patients treated during the HA operation. With most patients receiving treatment ashore where operations are limited to daylight hours, time is critical. Further, time personnel spend in transit comes at the expense of their contribution to operations or ability to deal with fatigue by resting, and by extension, their proficiency given the arduous workday.

The SSTP is formulated as a mixed-integer mathematical optimization model, the T-AH HA Transportation (T-AH HAT) model. It seeks to minimize a multi-objective merit function reflecting: (a) the degradation in mission performance occurring when personnel are not at their assigned mission sites during potential operational hours; (b) the degradation in personnel strength occurring as a function of time spent in transit or idle awaiting transportation; and, (c) the fixed and variable costs of transportation asset utilization.

The SSTP decision maker employing the T-AH HAT model is afforded the opportunity to weight the various objective function elements in keeping with their assessment of priorities. Given input criteria, the model produces an optimal plan for ship-to-shore movement, assigning passengers to vehicles and scheduling vehicle movement. The model reflects unique constraints such as limitations on T-AH flight deck utilization, and on embarkation and debarkation of personnel between T-AH and watercraft. The T-AH HAT model is implemented in Xpress-MP, with a supporting MS-Access database.

Our optimized schedules improve average duration of ashore mission site operations by between 9% and 13% compared to a set of pseudo-manually generated schedules (which appear generous compared to the actual manual schedules produced during recent operations). Over the course of an HA deployment, even minor efficiencies can translate into thousands of additional patients receiving medical care (e.g., COMFORT treated nearly 95,000 in 2007). Simultaneously, we are able to decrease average time spent by personnel in transit by between 16% and 43%.

Besides the single-day SSTP, this thesis devises an approximating algorithm to accommodate the allocation of a pre-specified number of helicopter flight hours, a monthly constraint, over a set of daily T-AH HAT mission scheduling problems. The utility of allocating flight hours among daily problems by this algorithm, instead of on a pro-rata or other arbitrary basis, is that flight hours are assigned based on where they will have the greatest impact in improving aggregate objective function value across the set of daily problems. For example, a set of T-AH HAT optimized schedules employing this algorithm improves, among other criteria, the number of fully manned mission site

operational hours by an additional 3% (on top off initial optimization gains) relative to optimized schedules employing the same gross number of flight hours but without reallocation between the individual problems.

The T-AH HAT model also promises to serve as an analytical tool in determining the impact on mission performance criteria of providing additional transportation capability to the T-AH. In preliminary analysis over three notional operating scenarios, the certification of a second flight deck helicopter landing spot was found to increase ashore mission site operating hours by 4%, while the addition of two high-capacity watercraft to the T-AH improved ashore mission site operating hours by 10%, both with regards to already optimized schedules.

The availability of the T-AH HAT model and implementation has been advertised to decision makers associated with an upcoming HA deployment of USNS MERCY (T-AH 19) in mid-2008, thus far with positive response from COMPACFLT personnel. Efforts to field the model and implementation aboard MERCY are ongoing. Thesis results are being shared with Mr. J. Zarkowsky, Director, Future Deployable Platforms at the Bureau of Medicine (Navy), and have been briefed to Mr. J. Kaskin, Director, Strategic Mobility & Combat Logistics Division, Office of the Chief of Naval Operations (N-42).

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LIST OF ACRONYMS AND ABBREVIATIONS

BLZ	Boat Landing Zone
DESRON	Destroyer Squadron
DR	Disaster Relief
h	Hours, as in 13:00h denoting a time of day
HA	Humanitarian Assistance
kts	knots
MIP	Mixed-Integer Program
MS	(Ashore) Mission Site
NGO	Non-Governmental Organization
nm	Nautical Miles
NPS	Naval Postgraduate School
SSTP	Ship-to-Shore Transportation Problem
T-AH	Hospital Ship
T-AH HA	Hospital Ship Humanitarian Assistance
T-AH HAT	Hospital Ship Humanitarian Assistance Transportation [model]

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I. INTRODUCTION

A. UNITED STATES NAVY HUMANITARIAN ASSISTANCE

USNS COMFORT (T-AH 20) commenced a four-month Humanitarian Assistance deployment to Central and South America on 15 June 2007 amid great fanfare, rating a White House press release and multiple public statements from President Bush in the weeks preceding and following the hospital ship's departure [The White House, 2007]. As of this writing, COMFORT's 2007 deployment is the latest in a series of Humanitarian Assistance (HA) and Disaster Relief (DR) operations which have proven to be operationally complex endeavors of significant strategic value.[1]

U.S. Navy HA and DR deployments in support Tsunami relief in 2005, and a subsequent HA deployment of USNS MERCY (T-AH 19) to Indonesia and neighboring countries in 2006, saved and bettered thousands of lives, effectively delivering a strategic communications message from the U.S. directly to foreign populations. These operations have also been unique in their inclusion of Non-Governmental Organization (NGO) partners. It has been noted hospital ships may be viewed as offensive participants in the so-called Global War on Terrorism "by supporting U.S. public information and public diplomacy efforts through direct and highly visible contact with individuals we may wish to influence" [McGrady, 2006].

The recently released strategic document "A Cooperative Strategy for 21st Century Seapower" elevates HA to 'core capability' status for the U.S. Navy, placing it among traditional roles, such as Power Projection and Sea Control, that collectively "comprise the core of U.S. maritime power" [Allen et.al., 2007]. The document also specifies that the expeditionary character of maritime forces places the Navy in a unique position among interagency and multinational HA and DR practitioners. This establishes

[1] The terms HA and DR are commonly used in conjunction, as in 'HA/DR', although deliberate HA operations may take place without regard to any specific disaster. COMFORT's 2007 deployment was an instance of deliberate HA, however, there was an intended DR training and preparedness element to the mission, recognizing the operational similarities between the two. While this thesis will focus on optimizing a process found in HA operations, results will be strongly applicable to DR.

two things: First, the Navy has a defined interest in HA; Second, the Navy recognizes there is an expectation it will bring the capabilities associated with expeditionary operations – robust planning, agility, communications capability and logistical might – to highly visible international HA efforts.

This performance expectation is particularly significant with regards to three groups: NGOs, host nation populations, and the media. NGOs have high expectations when they work with the U.S. military. In particular, they expect the military will bring capability and expertise in the very area NGOs find most constraining: logistics. If NGOs participate in a military operation and do not find the expected logistics capability and expertise, they will be less likely to work with the military in the future and may question the government's commitment to the operation.

Host nation populations, once selected to receive HA, have high expectations of the capability and efficiency of the U.S. government, and by extension, the military. The positive impact of successfully treating a host nation populace may be offset by the negative impact of unmet expectations, especially if the populace believes a lack of effort or operational efficiency on the part of HA providers is to blame for their disappointment. Perceptions by the populace of inefficient or unmotivated operations may be shaped by such factors as the number of hours ashore mission-site facilities are open during the day, the number of days spent at each mission site or host nation, the availability of pharmaceuticals, fair and orderly queuing processes governing access to treatment for patients at the mission-sites, and realistic transportation options for patients required to visit the Hospital Ship (T-AH) for surgery. These factors, in turn, are dependent upon optimizing such HA processes as transportation, personnel assignment, patient selection, material allocation, and mission-site organization.

Finally, HA operations will be subject to media scrutiny. The media will likely have more access to HA operations than to traditional combat operations, and the perception that HA operations are discretionary invites media analysis of the operation's value. A factor in whether the media will praise or criticize HA operations will be the media's perception of the operations as reflecting or lacking the expeditionary acumen and capability expected from the U.S. military. The latter was the case when, following

COMFORT's 2007 deployment, an article entitled "Feel-Good Diplomacy" appeared in the Baltimore Sun, cataloging the ways in which COMFORT did not deliver its full potential of medical assistance during the deployment [Little, 2007]. Figure 1 shows COMFORT at anchor while conducting HA operations in Haiti during the 2007 deployment.

Figure 1. Photograph of USNS COMFORT anchored offshore while conducting HA operations in Haiti during the 2007 deployment [Leavitt, 2007].

An additional and overarching motivation for an increased focus on HA performance is succinctly expressed by Rear Admiral Timberlake, United States Joint Forces Command (USJFCOM) Surgeon:

> The U.S. Military has always succeeded because we have great people – both line and medical personnel. We succeed in tasks we are given – like HADR – even without extensive planning. However, it often is accomplished at great personal cost in terms of time, effort, and stress. Each time, we seem to start all over again from scratch…We are not prepared or set up to do humanitarian assistance and disaster relief as efficiently as we could [Mosier and Orthner, 2007].

Prior to 2005, T-AH HA and DR deployments were relatively infrequent. Recent T-AH deployments have been rushed through a hasty planning process, necessarily so in the case of DR operations (e.g., following the 2005 Tsunami) but without good justification for deliberate HA operations. These operations have not benefited from the sort of

rigorous analysis that characterizes other military operations. With only limited experience in HA operations, realistic upper bounds for what can be accomplished during HA are unknown (making it difficult to characterize an operation as a success or failure). Further, bad practices could be solidifying during haphazard operations. There is recognition that past HA and DR operations have been muscled through by the devoted personnel involved, without much premium placed on operations analysis and efficiency, or much reliance on planning and doctrine [Mosier and Orthner, 2007]. Yet, as was the case with the 2007 COMFORT deployment, the operation was designed, in part, as a training mission. Training to inefficient practices potentially inhibits future performance when HA capability is applied to a critical DR situation.

Underscoring the strategic implications of future HA operations, the U.S. may soon be joined by another nation conducting medical HA from a hospital ship. The Chinese Navy has recently commissioned a hospital ship of its own (Figure 2). Whether the intention is for this vessel to fulfill a traditional hospital ship role in major military operations or to be a vehicle for HA and the projection of Chinese influence is unknown. The potential for competing U.S. and Chinese hospital ship-based HA in the developing world, or possibly combined operations in a DR setting, is fascinating. This entrance of a potential peer competitor, with what could be a combined force multiplying asset, to the practice of hospital ship operations further highlights the need for operationally efficient U.S. T-AH HA.

Figure 2. Chinese Hospital Ship Commissioned in 2007 [China Defense Today, 2007]

B. NAVAL HUMANITARIAN ASSISTANCE OPTIMIZATION

The necessity to live up to the claim that HA is a core capability for the Navy brings urgency and meaning to analytical efforts aimed at improving naval HA. This thesis develops a mathematical optimization model to assist key decision makers involved in naval HA in addressing one of many HA problems which would likely benefit from rigorous quantative analysis. Mathematical optimization models "represent problem choices as decision variables and seek values that maximize or minimize objective functions of the decision variables subject to constraints on variable values expressing limits on possible decision choices" [Rardin, 2000]. As such, problems which can be represented in terms of decisions and constraints are appropriate for mathematical optimization modeling.

There are unique aspects to T-AH HA that preclude the application of standard military operations models and doctrine. The T-AH represents both the launching point for medical personnel going ashore (analogous to an amphibious assault ship), yet with the added complication of also serving as one of several hubs of mission-objective activity. Specialized medical personnel and materials, along with logistics and communication capability, must be resourced in the correct proportion to meet the unique needs of the HA mission. NGOs are likely to contribute resources, especially personnel, but also impose unique constraints. Taken together, these factors make T-AH HA and DR operations an especially fertile area for the meaningful application of mathematical optimization.

In the case of COMFORT's 2007 HA deployment, complicated problems and time constraints frequently left decision makers without a means to make optimal decisions. Most clearly observed and understood by the author was the "ship-to-shore transportation problem" (SSTP), defined here as the daily need to determine transportation asset (helicopters, watercraft, land vehicles) routing and loading to effect movement of personnel and patients between ship and ashore mission site.[2] Among the

[2] The author spent three weeks aboard USNS COMFORT, taking part in HA operations in Belize, Guatemala and Panama.

T-AH HA problems which may benefit from optimization, in this thesis we address the SSTP because modeling the problem objectives and constraints does not require a specialized understanding of medical matters.

In addition to the SSTP, other tactical level problems faced daily during COMFORT's deployment included allocation of specialized personnel to remain on COMFORT or to staff ashore mission sites, management of patient queues and of services to be provided at mission sites, daily allocation of limited pharmaceuticals and other consumable material, and management of the scheduling, intake, treatment and release of surgical patients treated aboard COMFORT. Each of these areas presented challenges unique to T-AH HA operations. For instance, because surgical patients had to be discharged before COMFORT's scheduled departure from the host nation's waters, surgeries with longer recovery times had to be scheduled as early as possible during COMFORT's visit, and some otherwise feasible procedures were made infeasible by post-surgical recovery time constraints. This represents a unique variation of the *Robust Surgery Loading Problem* faced by hospitals everywhere and studied as an optimization problem, where utilization of operating theaters may be maximized by treating surgical assignments as a stochastic knapsack problem [Hans et.al., 2006].

In addition to these tactical-level problems, a host of complex weekly and mission-wide decisions had to be made, some before the COMFORT deployment commenced. Because COMFORT's deployment consisted of a series of six to seven-day visits in twelve different countries, many operational decision parameters changed on a weekly basis, and resources assigned to last through the deployment had to be apportioned among the visited countries (arbitrarily in some cases). Decisions made prior to the deployment included the selection of host nations to receive HA, the selection of mission sites within those host nations, designation of a range of medical and other services to be carried out during the HA, the assignment of personnel to COMFORT with the right skills to effect the selected services, and the scheduling of the deployment. The application of mathematical optimization (and Operations Research in general) to any of these areas would likely contribute to improved HA performance for the Navy.

C. HOSPITAL SHIPS AND THE TRANSPORTATION PROBLEM

We address the SSTP (defined in section B above) faced by a T-AH conducting HA operations in situations where the ship is not able to berth at a pier in the host nation (a common occurrence resulting from the ship's relatively large draft and port or pierside support limitations in developing countries). While ship-to-shore movement would normally be one of the expeditionary capabilities making naval forces invaluable to HA, the T-AH faces some inherent obstacles relating to the ship's design, limited indigenous capabilities, and doctrinal shortcomings (discussed below). Aggravating the inherent obstacles during past deployments has been the use of a manual transportation scheduling process unsuitable for quickly dealing with a complex and time-sensitive problem. Further, T-AH HA missions have not generally been staffed by the Navy's expeditionary experts (those familiar with the Marine Corps ship-to-shore movement doctrine), so unfamiliarity with complex logistical problems may have impeded decision makers.

In this context, a typical SSTP includes scheduling two helicopters, several watercraft (with different speeds, capacities, and abilities to function in certain sea states), and an assortment of ground vehicles to move over two-hundred T-AH personnel and patients between the ship and several mission sites, often traveling through intermediate nodes. In the majority of cases, this is not a trivial problem to optimize. Especially problematic for the manual scheduler is understanding the tradeoff between different modes of transportation and resisting the temptation to inefficiently simplify the problem by attempting to move all personnel *en masse* first to an intermediate node, and then out to mission sites or the ship.

During COMFORT's 2007 deployment, sub-optimal transportation schedules were observable to, and felt by, the hundreds of medical and support personnel who spent frustrating hours assembled together but unable to maximize mission accomplishment because transportation constraints and scheduling lapses left them marooned at a boat landing zone or loitering at a staging area on the ship, sometimes for as long as 3-4 hours

at a time. Such situations are especially poignant when one considers the opportunity cost of allowing specialized medical personnel, some of them NGOs, to sit idle while waiting for transportation.

1. Hospital Ship Design and Capabilities

The two U.S. Navy hospital ships, MERCY and COMFORT, were initially constructed and operated as oil tankers under different names, going through a conversion process to become hospital ships in the mid 1980's. Central to the T-AH SSTP is the fact that the T-AH was not intended to operate as a stand-alone platform, or as the Command ship in an operation involving other assets. Published Navy doctrine on T-AH operations [Department of the Navy, 2004] specifies:

> The preferred method of moving patients is by helicopter. In port, patients can be removed via the gangways (if pierside). If anchored, the ship can move patients to the port and starboard side ports for transfer to surface craft. The hospital ship owns neither air nor surface craft. Ultimate responsibility for providing patient transportation to and from the hospital ships belongs to the theater commander. The OPLAN [Operational Plan] should detail the transportation plan. (Author's emphasis added)

While this doctrine is perfectly appropriate for a T-AH operating in conjunction with a large, deployed combat force, it does not serve the T-AH operating in a HA capacity where neither the combat force nor its associated logistics capacity are present.

Recognizing the T-AH's shortcomings, effects have been made to provide the ships with some indigenous transportation capability. Prior to MERCY's 2006 deployment, a temporary helicopter shelter was installed. The addition of embarked helicopters was intended to allow the T-AH to "operate flexibly without support" [Horvath, 2006]. While providing shelter for embarked helicopters, this structure reduced the number of landing spots on the T-AH from two to one. Also added at this time were two small watercraft, less than ideal for ship-to-shore movement due to their slow speed, limited capacity, difficultly embarking and debarking passengers, limited operability in rough seas, and inability to protect passengers (some who will be sick or injured patients) from the elements. Identical modifications were made to COMFORT.

As of early 2008, plans are in place to further modify the T-AH's indigenous transportation capability. A near-term modification will be the replacement of the current helicopter shelter with a permanently mounted hanger. Directly significant to one of the constraints currently faced in the SSTP, the layout and certification of the flight deck will be addressed to allow for two landing spots. Also under study, but without a definitive implementation date set, is the addition of two 'patient tender' watercraft to the T-AH. Each patient tender will have a capacity for 150 personnel, be enclosed to protect the passengers from the elements, move at a speed of 14 kts, and be embarked and disembarked from the T-AH via a boat davit system [Zarkowsky, 2007]. The planned patient tenders will be vastly superior to current watercraft which expose personnel to the elements, embark and disembark personnel through a precarious process alongside the T-AH, and move slowly. While funded, patient tender procurement and installation is currently delayed by a shortage of available units from manufactures. Analysis of the impact of patient tenders will be discussed in Chapter III.

2. Previous Hospital Ship Humanitarian Assistance Operations

In January 2005, MERCY deployed as a part of Operation Unified Assistance to take part in tsunami-relief operations in Southeast Asia, treating Indonesian patients between 5 February and 14 March. Arriving well over a month after the tsunami had struck, the majority of patients seen by MERCY personnel received treatment for conditions unrelated to the tsunami, rendering the mission largely HA (vice DR) in nature. Remaining deployed, MERCY went on to conduct deliberate HA operations in areas unrelated to the tsunami, and also to respond to emergent DR situations over the next several months. A Center for Naval Analysis report on the 2005 deployment concluded "The major non-medical constraints on the medical mission were physical access to the hospital ship, helicopter life capacity, mission scheduling issues, and force protection precautionary measures" [Morrow and McGrady, 2006]. Helicopter lift was the sole transportation means on or off MERCY in some operational areas, while boat and helicopter operations were possible in other areas, with boats being obtained from the host nation. The report notes a consequence of the limited transportation capacity and the

requirement to return all personnel to MERCY each night was that ashore operations shut down as early as 15:00h so personnel could muster and await their return trip. This not only reduced time ashore to conduct the primary mission of medical treatment, but also prevented MERCY personnel from attending evening planning meetings with shore-based NGOs. Finally, the report also notes that on days when the helicopters were not operated (possibly due to maintenance or inclement weather) or were tasked to effect transfer of rotating medical personnel, there were no patient admissions aboard MERCY.

In April 2006, MERCY commenced another HA deployment, this time to the Philippines, Bangladesh, Indonesia, and East Timor. Utility boats and the aforementioned helicopter shelter to support embarked helicopters were added to MERCY prior to the deployment. The utilization of utility boats to achieve a portion of the movement between ship and shore represented a significant change in the SSTP MERCY would face in 2006 compared with 2005. Utility boats offered medical providers ashore a flexible and responsive means to move personnel, patients and material between ship and shore to meet emergent requirements [Schiemel, 2007]. Despite this, transportation between ship and shore still represented a significant constraint on the mission, "significantly [reducing] the number of hours available to conduct medical operations ashore on any given day" [Strauss, 2007, p.25]. In the case of one operating area, shallow waters forced MERCY to remain more than 30 nm offshore, relying completely on helicopters for transportation. In other cases, MERCY came much closer to shore and utilized both boats and helicopters, but it was calculated that, as utilized, combined transportation assets were rarely allowed more than 150 personnel to travel to ashore mission sites during the day [Strauss, 2007, p.35].

It is clear the transportation challenges present during COMFORT's 2007 deployment had been previously identified during MERCY's HA deployments. While analysis has been done on the benefit of increasing transportation capability, no analysis has been found regarding optimization of the schedule for existing transportation assets. A Naval Postgraduate School (NPS) Information Systems thesis dating to the initial years of MERCY class operations recommends addition of a decision support system be added to the ship's information systems to optimize the loading of evacuation assets (helicopters

and boats), and noted the 'stubby pencil' is the current means of assigning outgoing patients to transportation assets [Sosh, 1988, p.85]. During T-AH HA deployments through 2007, the 'stubby pencil' remained the scheduler's only tool.

3. Manual Solutions to the Transportation Problem

A manual process for devising transportation schedules must be used absent the availability of decision support tools. The focus of manual scheduling, when faced with a complex and time-consuming problem, inevitably becomes finding a feasible solution within the allocated timeframe without regard to optimality. Manual scheduling has specific drawbacks in four areas: it is a time consuming process, it leads to inefficient simplifications of the schedule or overly conservative decisions, varying vehicle capacities and group sizes make optimal vehicle-group parings unobvious, and it does not lend itself to quantitative analysis of other operational decisions due to a lack of analytical formality. All of these drawbacks were observed first-hand by the researcher and other NPS personnel who participated in the COMFORT 2007 deployment. Discussion of the four areas of drawback follows.

1) Time Consuming Process. Manual generation of the following day's transportation schedule may take hours of time and typically occurs late in the evening. Schedules cannot always be devised in advance because they are dependent on operational parameters, such as the specific number of personnel and patients moving between ship-and-shore, which are themselves reevaluated by planning personnel daily. Specific decisions defining these operational parameters for the following day are not made until late in the prior day when the outcome of that day's operations has been accessed. Time consumed by the scheduling process also comes at the expense of other planning and attention to command and control functions, as the individual responsible for transportation planning will have many other staff responsibilities.

2) Inefficient schedule simplifications and conservative decisions. In order to manually deal with a complex scheduling problem, planners may utilize inefficient simplifications of the process. For example, the planner may break the schedule for personnel returning to the ship into two distinct phases, first executing the

ground transport all personnel from several mission sites to a consolidated Boat Landing Zone (BLZ, generally a transfer point for personnel between watercraft and ground vehicles), and only then beginning to execute the transfer of personnel from the BLZ to the ship by watercraft. While not having to consider concurrent scheduling of watercraft and vehicles simplifies the problem for the planner, it does not lead to optimal movement of personnel. The practical result is that personnel stop work and depart their mission sites earlier than necessary, only to loiter unproductively (and unhappily) at a BLZ. Another simplification employed by the planner may be the implementation of a conservative schedule, for example, by having personnel muster or shut down operations earlier than necessary, loiter at a transshipment point longer than necessary, or have vehicles ready earlier than necessary in order to deal with uncertainty created not by legitimate variance in travel times or operations, but simply by imprecision in the process of manual calculations and a planner's instinct towards conservatism.

3) Unobvious vehicle-group parings. Another shortcoming of manual scheduling derives from the difficulty in recognizing when vehicle-group parings are not optimal, or whether alternative vehicle-group parings exist. Manual combinatorial analysis is difficult, and the possibility exists a planner may not realize the most efficient vehicles to passenger group paring. For example, consider a BLZ as the common transshipment point for three different-sized groups of personnel going to three different mission sites, and a fleet of vans with varying capacity available for transportation. It may be tempting for the planner to simplifying the scheduling by assigning a third of the vehicles to service each personnel group. This assignment could leave empty seats on the arbitrarily assigned vehicles going to one destination, while forcing some passengers from a larger group to wait for vehicles assigned to their group to return and make a second trip.

4) Lack of analytical formality. The manual scheduling process does not lend itself to analysis of operational decisions, such as the anchoring position of the T-AH, the trade-off between using helicopter or watercraft and ground transportation, or the procurement of additional host-nation transportation assets. The Commander is less

likely to rely on an imprecise manual process to inform his or her operational decisions than he or she would be if formal, quantative analysis were available from an automated decision support tool.

D. THESIS GOALS AND OUTLINE

This thesis seeks to develop and implement a mathematical optimization model to provide a decision support tool to decision makers aboard the T-AH responsible for the SSTP. It is also intended to fulfill two other purposes: to provide a quantitative tool for the evaluation of notional transportation arrangements and potential T-AH modifications beyond the scope of the daily SSTP, and to identify other aspects of T-AH HA that are good candidates for the future application of Operations Research techniques.

Manual SSTP solutions observed during COMFORT's 2007 deployment were suboptimal. To deal with the complex, time-sensitive and dynamic requirement to devise transportation schedules, a decision support tool, based on the model defined in this thesis, should be placed into the hands of decision makers during future T-AH deployments. This tool will provide the decision makers with optimized schedules addressing the daily SSTP. The decision maker will be able to specify the relative importance of competing objective function criteria in the optimization.

Matters beyond solving the daily SSTP may be addressed. For example, should resources be expended to increase the number of landing spots on MERCY and COMFORT from one to two? How beneficial would it be to commit an amphibious ship to supporting T-AH HA operations? How much priority should be given to the installation of patient tenders aboard MERCY and COMFORT? To help answer questions of this nature, our mathematical models serve as a quantitative tool for the evaluation of transportation-capacity affecting decisions.

Finally, as noted in Section A, T-AH HA operations are fertile ground for the meaningful application of Operations Research techniques, particularly mathematical optimization. While this thesis is focused on the SSTP, the techniques for evaluating problem solutions in terms of mission performance will be generally applicable to other

areas of HA analysis. As such, it is intended that this thesis will provide a baseline for further Operations Research study of HA and DR.

The remainder of this document is organized as follows: Chapter II explains how we formulate the SSTP as a mathematical model, first by discussing the problem in general, then in detail with a focus on the objective function, and finally by providing the mathematical formulation. Chapter III provides quantative analysis of the efficiencies and insights gained by using the model described in Chapter II. To accomplish this analysis, criteria for evaluating SSTP solutions are defined, and SSTP scenarios are introduced. Chapter III also uses the model to perform analysis of potential modifications to the T-AH class of ship. Chapter IV concludes this document by summarizing computational results and highlighting their significance in light of the overall rational presented in Chapter I for applying mathematical optimization to HA. Discussion of the model's implementation, dissemination of computational results, and recommendations for follow-on work is also included.

II. MODELING APPROACH

This chapter introduces the T-AH HA transportation (T-AH HAT) model that utilizes mathematical optimization to devise a schedule for ship-to-shore movement for the T-AH conducting HA from offshore. Because we can reasonably represent many important facets of the SSTP in terms of quantifiable objectives and constraints, mathematical modeling is an appropriate means to address the SSTP.

A. CHARACTERISTICS OF THE TRANSPORTATION PROBLEM

This section discusses several concepts and problem specifications underlying the mathematical model (to be stated formally later in this chapter).

One of these concepts is referred to as *time period*. In order to represent the dynamics of the SSTP over time, continuous time is represented as a discrete set of *time periods*. For example, if the operations to be modeled begin at 06:00h with a user-defined period length of 10 minutes, the first time period corresponds to the continuous time interval between 06:00h and 06:10h, the second to the time interval between 06:10h and 06:20h, and so on.

Another key concept is *group*, which we define as one or more people with a like starting position, destination, and time at the origin, among other parameters. We shall see groups will also be associated with varying weighting schemes (penalties or incentives associated, e.g., with time delays) in the objective function.

We now enumerate the specific entities (and their characteristics) in the SSTP that are captured in the T-AH HAT model:

- There exists a discrete set of locations where personnel and vehicles may arrive, depart, or loiter. Each location is represented as a *node* in the topographical representation of the SSTP.

- Each node is defined by a name, number of helicopter landing spots, number of watercraft embarkation or debarkation spots, and whether or not it is an acceptable location for helicopter shutdown.
- Each *vehicle* is defined by identifier, starting node, type, and capacity.
- General vehicle types include helicopters, ground vehicles, and watercraft.
- Nodes may be connected by node-to-node paths called *arcs*, forming a network.
- Some arcs are not feasible for some vehicle types.
- Each arc has a transit time associated with it for each vehicle type that can feasibly use the arc.
- The speed of each vehicle type is accounted for to compute its travel time between nodes, if feasible.
- Each vehicle is further characterized by relative fixed and incremental operating costs.
- Incremental vehicle costs are based on the number of time periods of movement for ground vehicles and watercraft. For helicopters, incremental operating costs are incurred for every time period they are at any node not designated as an appropriate helicopter shutdown location, whether traveling or loitering on the ground.
- When all vehicle types are considered, the network must be strongly connected (a feasible path exists from each node to all others in the network).
- The helicopter shelter on a T-AH is a separate node from the T-AH flight deck, and the travel time between these two nodes corresponds to the time required to move the helicopter and change its condition from operational to inactive, or vice-versa.

- The number of helicopters present at a node is constrained by the number of helicopter landing spots at that node.
- Helicopters must spend the time period following arrival at a node on the ground at that node (accounting for time required for loading, unloading, and refueling).
- The number of watercraft arriving or departing from a node in the same time period is restricted by the number of watercraft embarkation or debarkation spots; multiple watercraft may loiter at a node with a single spot by mooring outboard of one another.
- Each group is defined by identifier, size (number of people in the group), starting node, destination node, time of initial availability to travel from starting node, desired arrival time at destination node, and mandatory (i.e., latest feasible) arrival time at destination node.
- Each group is further characterized by the relative importance of several potentially competing objectives: arrival at the destination node by the desired arrival time, minimization of time spent in transit, and delay at starting node before commencing transit.
- Individual members of a group do not necessarily travel together.
- All personnel in all groups must reach their destination node by the latest feasible arrival time. Otherwise, the problem is deemed infeasible.

B. SSTP AND THE GENERAL VEHICLE ROUTING PROBLEM

Our SSTP is a variant of the often-discussed Vehicle Routing Problem (VRP) [Toth and Vigo, 2001]. It particularly resembles a VRP with time windows, pick-ups and deliveries. Specific issues our VRP must address include the concept of personnel groups, a multimodal transportation network with transfers, node capacities (such as those for helicopters at the T-AH and other landing zones), and the fixed-charge for vehicle utilization, which implicitly designs the system capacity.

The VRP has received considerable attention in the Operations Research discipline. Recent academic papers have focused on improved algorithms for efficient problem solution, particularly genetic and hybrid-genetic algorithms [Park, 2000]. Because we have generally been able to reach global-optimal solutions within an acceptable amount of time, heuristics have not been necessary. Nonetheless, it is noted that heuristic algorithms could become necessary if the SSTP grew to consider significantly more transportation assets or nodes, perhaps across a theater of HA and DR operations.

C. OBJECTIVE FUNCTION DESCRIPTION

This sections details the composition, mechanics and rationale behind the T-AH HAT model's objective function. This function seeks to minimize 'transportation schedule cost', which in fact comprises multiple individual objectives. Therefore, our model is a multi-objective optimization problem in which we adopt a weighted-sum (of objectives) approach (see, e.g., Ehrgott [2005, p.65]).

We consider two general categories of transportation schedule cost. One is the cost of degraded mission performance if personnel and patients are not transported to their destinations in a timely fashion. The other is the cost (monetary or otherwise) of utilizing transportation assets. Both of these cost categories are nuanced by a variety of subcategories, and by tradeoffs created by the relative weights assigned to each criteria.

1. Degraded Mission Performance from Late Arrival

Mission performance is a function of, among other things, time spent by providers treating patients ashore and aboard the T-AH. Treatment of patients relies on transportation of providers and surgical patients between shore and T-AH. When transportation becomes the active constraint on provider time spent treating patients, a mission performance cost is incurred. The model establishes a *desired arrival time* for providers and patients who require transportation. The *desired arrival time* is defined as the time at which the mission planner believes the personnel should arrive at their destination in order to achieve orderly and reliable mission performance given non-

transportation constraints. It is assumed that if a transportation solution can be found that delivers all providers and patients to their destination by the *desired arrival time*, no cost in degraded mission performance is incurred. *Desired arrival time* is implemented in the model by a *late arrival penalty* charged per unit of time each person (mission personnel or patient) is not at their destination once the *desired arrival time* designated for their group has been reached. The decision maker selects a base *late arrival penalty* for each group, reflecting the relative importance placed on timely arrivals for personnel in that particular group. During preprocessing, the model associates the base *late arrival penalty* with the first *time period* in which each respective individual would be late, and then calculates exponentially increasing penalties for later time periods as a function of the base *late arrival penalty*, the number of time periods beyond the *desired arrival time*, and an exponential factor (see Figure 3). Marginal *late arrival penalties* are calculated as:

$$\Delta AP(t) = \begin{cases} 0, & \text{if } t \le d \\ b_{LAP} + b_{LAP}^{\,2^{\frac{t-d}{l-d}}}, & \text{if } t > d \end{cases} \qquad (1.1)$$

where $\Delta AP(t)$ is the marginal per-person penalty incurred if arrival in period t has not occurred, d is the desired arrival period, l is the latest arrival period, and b_{LAP} is the baseline *late arrival penalty*. Note that, for clarity, we have dropped the group sub-index "g" in all parameters.

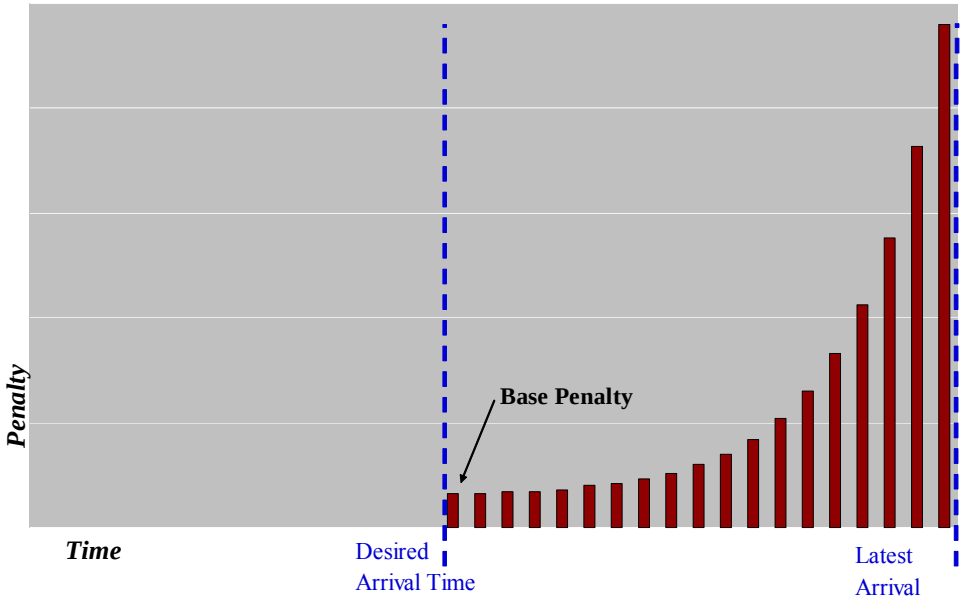

Figure 3. Marginal *late arrival penalty*. The graph shows the marginal penalty incurred per person in each time period the person is late.

2. Expedite Arrival Penalty and Delay Initial Departure

There are two competing refinements to the *desired arrival time* that a decision maker may employ. We will refer to these two refinements as "expedite arrival" and "delay initial departure". Refinement *expedite arrival* is characterized by adding the stipulation that transportation schedule solutions that deliver personnel in a specific *group* to their destinations sooner are preferable to those that take longer, irrespective of whether or not *desired arrival time* is met. Two assumptions underlie this refinement: The first assumption is that there is some mission performance benefit derived from personnel arriving at their destination earlier than the *desired arrival time*; this may occur because it is feasible to begin operations earlier than planned, or because personnel may use the additional time at destination to be better prepared for when operations do begin as scheduled. A second assumption is that performance and morale of providers, and the condition of patients, will be inversely proportional to time spent in transit. *Expedite*

arrival is implemented in the model through an *expedite arrival penalty* charged per unit of time each person is not at their destination, regardless of whether *desired arrival time* has been reached (see Figure 4). This penalty must, at a minimum, ensure the quicker transportation route will be chosen over the longer route when mission performance and transportation costs are otherwise equal or nearly equal. The decision maker can scale the penalty to reflect the degree to which he or she favors transportation solutions with earlier arrivals. If the penalty is made very large, it will eventually overwhelm *desired arrival time* and transportation cost considerations, leading to selection of the schedule with the earliest feasible arrival times. The intention, however, is for the penalty to be used in a more nuanced fashion. There is utility in applying the *expedite arrival penalty* in the objective function at a low level even if the decision maker does not specifically desire early arrivals; the penalty ensures that quicker routes will be chosen over slower routes, ceteris paribus. Marginal *expedite arrival penalties* are calculated as:

$$\Delta EAP(t) = b_{EAP} \quad \forall t \qquad (1.2)$$

where $\Delta EAP(t)$ is the marginal per-person penalty incurred if arrival in period t has not occurred, and b_{EAP} is the baseline *expedite arrival penalty*. Again, this penalty will be made group-dependent in our formulation below.

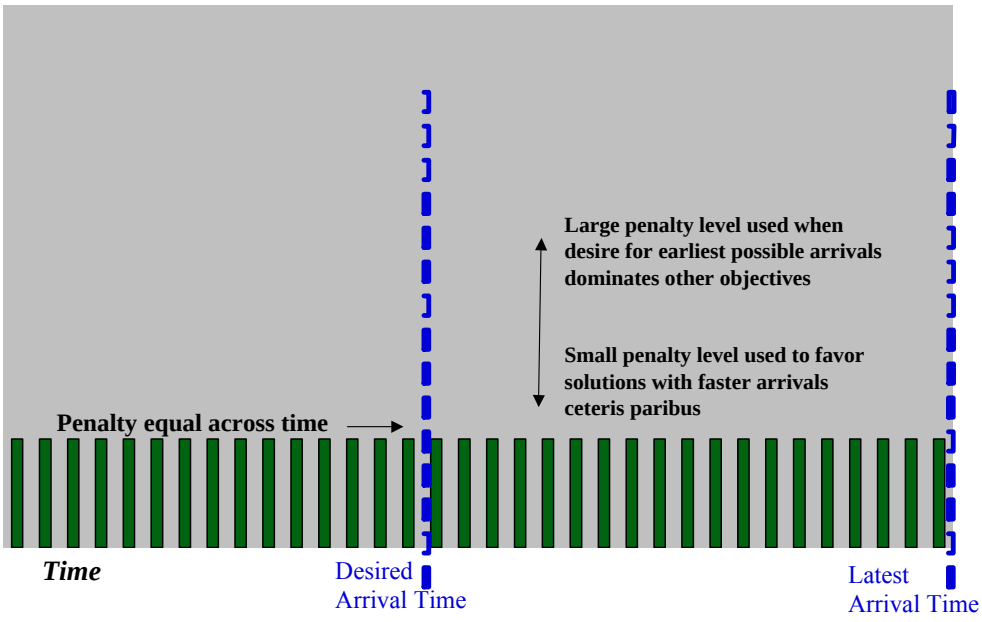

Figure 4. Marginal *expedite arrival penalty*. The graph shows the marginal penalty incurred per person in each time period the person has not arrived at their destination.

Refinement *delay initial departure* is characterized by favoring transportation schedule solutions which have a later initial departure time for personnel in a specific *group* from their starting position, compared to those with an earlier departure, assuming both allow for arrival by the *desired arrival time*. The assumptions that any mission performance benefit derived from an early arrival is outweighed by the benefit of allowing personnel to rest (if originating on the T-AH) or continue working (if originating at a mission site) underlies this refinement. The *delay initial departure* refinement is implemented through a *delay departure incentive* (inventive vice penalty because cost is being subtracted). The *delay departure incentive* is established by a user defined base incentive, and is then awarded, in linearly decreasing quantities, for each period all members of the designated *group* remain together (see Figure 5). Marginal *delay departure incentives* are calculated as:

$$\Delta DDI(t) = \begin{cases} 0, & \text{if } t > d \\ b_{DDI}\dfrac{d-t}{d-a}, & \text{if } t \le d \end{cases} \qquad (1.3)$$

where $\Delta DDI(t)$ is the marginal per-person incentive earned if the person's group remains together at their origin in period t, d is the desired arrival period, a is the group's first period of availability in the problem, and b_{DDI} is the baseline *delay departure incentive*. As before, the coefficients in equation (1.3) are group dependent.

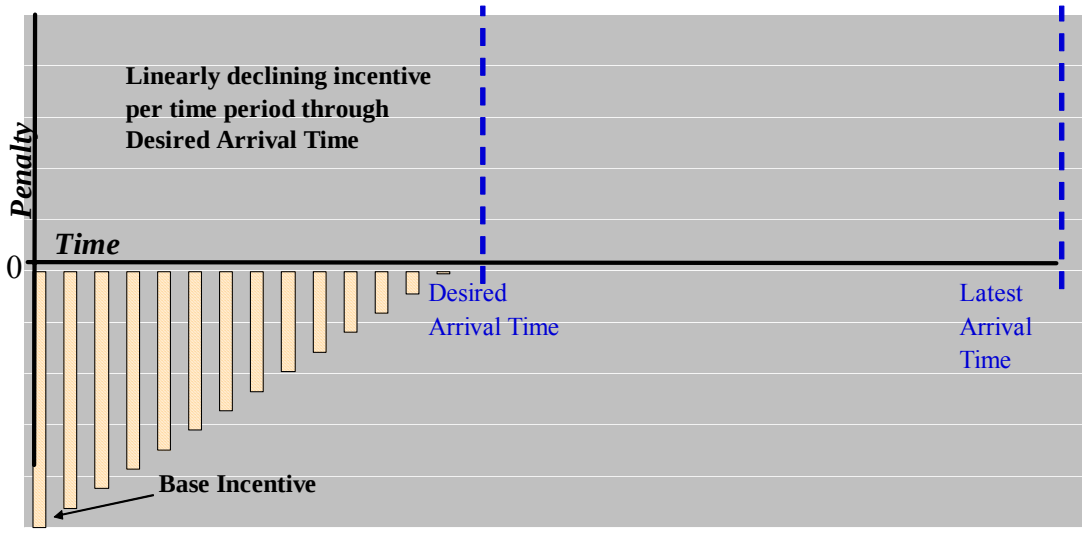

Figure 5. Marginal *delay initial departure*. The graph shows the marginal incentive awarded per person in each time period the person's group remains together at their origin.

A notional example of the combined potential effect of the two penalties and the incentive described above is depicted in Figure 6, with the cumulative effect of each penalty (or incentive) represented as a separate line. In this example, b_{LAP} = 16, b_{EAP} = 10, and b_{DDI} = 50. While a strict hierarchy of penalties does not exist in our model (scaling many competing penalties is left up the user), the eventual dominance of one objective is desired. Because moving personnel in a timely fashion to their required

destination is our founding objective, the *late arrival penalty* is designed to outweigh all others by the latest arrival time. This is the rationale for exponentially increasing the *late arrival penalty*. That is, the operating costs for vehicles or the incentive to delay departure should never create a situation where the optimal solution does not involve getting personnel to their destination eventually, assuming doing so is feasible (although it is possible the user could input a disproportionately large penalty or incentive working against the *latest arrival time*).

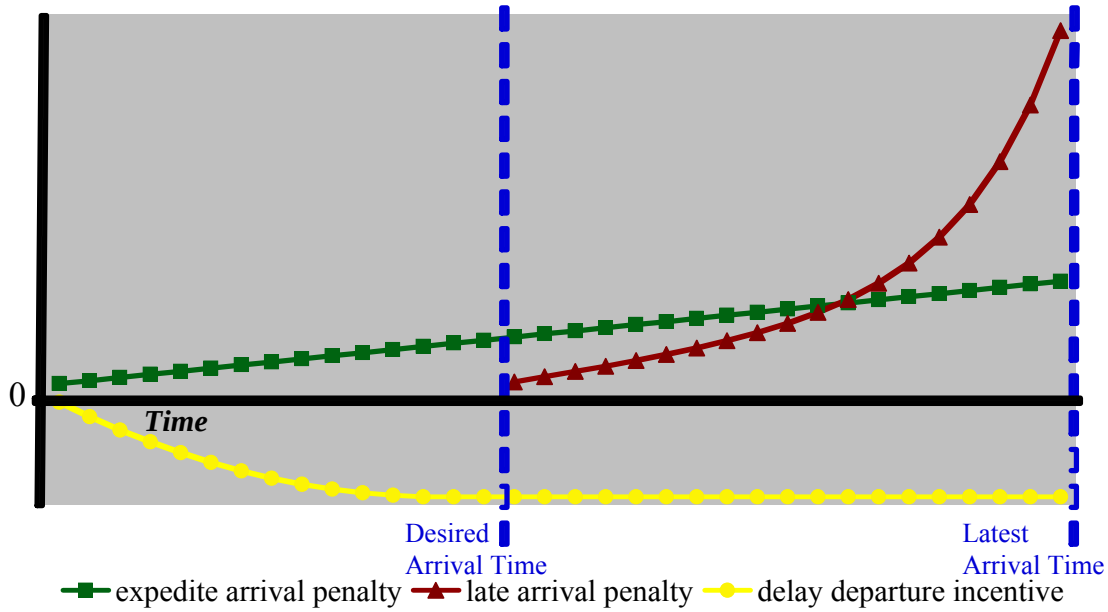

Figure 6. A notional example of the combined potential effect of the two penalties and the incentive described in this section (each shown cumulatively).

3. Transportation Asset Costs

Operating costs for transportation assets are also modeled in the objective function. These costs fall into two general categories: fixed and variable. The fixed cost associated with a transportation asset is incurred if the asset is ever used during the modeled timeframe. The variable cost is incurred per time period the asset is in motion (with an expended definition discussed below with regard to helicopters).

Regarding embarked helicopters, the fixed cost in our model represents the costs in personnel and required maintenance stemming from preparing the helicopter for flight and then returning it to a maintained condition. By setting a relatively high fixed cost for helicopter utilization, the decision maker can ensure a helicopter is brought out of its shelter and operated only when cost effective towards meeting operational goals. The variable cost associated with helicopter utilization is incurred during every time period the helicopter is not at a user-designed node where it can shut down (presumably the T-AH deck or shelter in most cases), thus any time spent flying or loitering at other nodes is considered to incur variable cost. If host-nation or non-embarked helicopters are available, the decision maker has the option to designate these as zero cost assets to maximize their utilization, or to assign them costs equivalent or in some relative proportion to those of the embarked helicopters to achieve the desired distribution of work.

While the actual monetary costs (in personnel, training, capital equipment, fuel, repair parts) associated with operating embarked helicopters are hidden from (and irrelevant to) the planner, a constraint on the number of flight-hours per month serves as a proxy for all the hidden costs and is of real concern to planners. The decision maker may use both the fixed and variable costs assigned to embarked helicopters to limit helicopter utilization to a level commensurate with the monthly fight hour constraint. A discussion of techniques to apply the monthly flight hour constraint to daily transportation problems is presented in Chapter III, Section D.

Regarding watercraft and ground vehicles, both fixed and variable costs are potentially needed to model the way scheduling of these assets will be important to the planner. Government owned assets, such as the watercraft indigenous to the T-AH or vehicles made available by the U.S. embassy in the host nation, are not likely to present costs relevant to the planner. Some variable cost may be applied to these assets simply to limit their utilization, although it is unlikely the planer would scale these costs to compete with other mission performance criteria like late arrivals. More significant is the contracting for local watercraft and vehicles. Because a wide range of contracting schemes exists, the fixed and variable costs for locally procured assets in the model may

represent different things depending on the particular situation. For example, a fixed-price contract costing a set dollar-amount per day for watercraft service between the T-AH and a BLZ, regardless of how many trips were made, would be represented by a fixed cost only. Conversely, if contracted watercraft were charged to the ship purely on a per-trip basis, this would be modeled through the variable cost mechanism.

D. MATHEMATICAL FORMULATION

This section describes the Hospital Ship Humanitarian Assistance Transportation (T-AH HAT) model, a weighted-sum, multi-objective, mixed-integer optimization model.

1. Sets and Indices

t,	period of time, for $t \in T$. All periods have the same duration, e.g., 15 minutes.
n, n',	nodes, for $n, n' \in N$. May refer to ship, mission site, or transshipment point.
g,	group, for $g \in G$. A group consists of personnel with a like starting point and destination.
v,	vehicle, for $v \in V$. May refer to either a helicopter, boat, or land transport.
N_h,	subset of N where a helicopter is not able to shut down.
V^H,	subset of V containing only helicopter vehicles.
V^W,	subset of V containing only watercraft vehicles.
$AV_{v,n,n'}$,	Subset of triplets (v, n, n') where vehicle v can travel from node n to node n'.

2. Parameters (Units)

$Atime_{v,n,n'}$,	Number of time periods it takes vehicle *v* to travel from node *n* to node *n'* (periods).
$Gorigin_g$,	node where group *g* originates (node index).
$Gdestination_g$,	destination node for group *g* (node index).
$Gsize_g$,	number of personnel in group *g* (persons).
$Gavailable_g$,	time period when group *g* initially becomes available (periods).
$GdesiredArrival_g$,	time at which group *g* is desired to arrive at its destination node (periods).
$GlatestArrival_g$,	time by which group *g* must have arrived at its destination node (periods).
$GbArrPenalty_g$,	base penalty per person in group *g* who has not arrived after $GdesiredArrival_g$ (penalty points). Same as b_{LAP} in equation (1.1).
$GmovePenalty_g$,	penalty per time period and per person in group *g* who has not arrived at destination regardless of desired arrival time (penalty points). Same as b_{EAP} in equation (1.2).
$GbDelayDepIncent_g$,	base incentive (reward) in the time period group *g* initially becomes available, per person, for leaving entire group at their origin (negative penalty points). Same as b_{DDI} in equation (1.3).
$NlandingZones_n$,	number of landing zones at node *n* (landing zones).
$NdockSpaces_n$,	number of dock space for simultaneous loading or unload of passengers at node *n* (dock spaces).

$Vavailable_v$, time period when vehicle v initially becomes available (periods).

$Vorigin_v$, node where vehicle v originates (node index).

$Vcapacity_v$, maximum transportation capacity of vehicle v (persons).

$VfixedCost_v$, cost to make vehicle v available for service (penalty points per vehicle).

$VperiodCost_v$, variable cost (per time period) to utilize vehicle v (penalty points).

3. Derived Sets and Data (Units for Derived Data Only)

T_v, subset of T when vehicle v is available.

$$T_v = \{t \in T \mid t \geq Vavailable_v\}$$

TA_g, subset of T where group g is available prior to their latest feasible arrival time.

$$TA_g = \{t \in T \mid Gavailable_g \leq t < GlatestArrival_g\}$$

TE_g, subset of T where group g is available prior to their desired arrival time.

$$TE_g = \{t \in T \mid Gavailable_g \leq t < GdesiredArrival_g\}$$

TL_g, subset of T where group g is late if not at destination.

$$TL_g = \{t \in T \mid t > GdesiredArrival_g\}$$

$Gdelta_{g,n,t}$, number of personnel in group g initially available at node n at time t (personnel).

$$Gdelta_{g,n,t} = \begin{cases} Gsize_g, & \text{if } n = Gorign_g, t = Gavailable_g \\ 0, & \text{otherwise} \end{cases}$$

$Vdelta_{v,n,t}$, one if vehicle v initially available at node n at time t (binary).

$$Vdelta_{v,n,t} = \begin{cases} 1, & \text{if } n = Vorign_v, t = Vavailable_v \\ 0, & \text{otherwise} \end{cases}$$

$GarrPenalty_{g,t}$, Marginal penalty in period t per person in group g who has not arrived after the desired arrival time (penalty points). Calculated as in equation (1.1) where $b_{LAP} = GbArrPenalty_g$, $d = GdesiredArrival_g$, and $l = GlatestArrival_g$.

$GdelayDepIncent_{g,t}$, Marginal incentive in period t per person for leaving entire group g at their origin (negative penalty points). Calculated as in equation (1.3) where $b_{DDI} = GbLateDepIncent_g$, $d = GdesiredArrival_g$, and $a = Gavailable_g$.

4. Decision Variables (Units)

$GW_{g,n,t}$, number of personnel in group g waiting at node n at time t (personnel).

$GX_{g,v,n,n',t}$, number of personnel in group g transported by vehicle v from node n to node n' leaving at time period t (personnel).

$GU_{g,t}$, number of personnel in group g who have not arrived at their destination by time t (personnel).

$VW_{v,n,t}$, one if vehicle v is waiting at node n at time t, zero otherwise (binary).

$VX_{v,n,n',t}$, one if vehicle v travels from node n to node n' leaving at time t, zero otherwise (binary).

VS_v, one if vehicle v is utilized during the mission day, zero otherwise (binary).

$Together_{g,t}$, one if group g remains together at their origin at time t, zero otherwise (binary).

5. Mathematical Formulation of T-AH HAT Model

Objective Function

$$\begin{aligned}\min \quad & \sum_{\substack{g\in G\\ t\in TL_g}} (GarrPenalty_{g,t} GU_{g,t}) + \sum_{\substack{g\in G\\ t\in TA_g}} (GmovePenalty_g GU_{g,t}) \\ & + \sum_{v\in V} (VfixedCost_v VS_v) + \sum_{\substack{n,n'\\ v\in AV_{v,n,n'}\\ t\in T_v}} (Atime_{v,n,n'} VperiodCost_v VX_{v,n,n',t}) \\ & + \sum_{\substack{n\in Nh\\ t\in T_v\\ v\in V^H}} (VperiodCost_v VW_{v,n,t}) - \sum_{\substack{g\in G\\ t\in TE_g}} (GdelayDepIncent_{g,t} Together_{g,t})\end{aligned} \tag{2.1}$$

Constraints

$$\sum_g GX_{g,v,n,n',t} \le Vcapacity_v VX_{v,n,n',t} \quad \forall v,n,n',t \mid v \in AV_{v,n,n'}, t \in T_v \tag{2.2}$$

$$VX_{v,n,n',t} \le VS_v \quad \forall v,n,n',t \mid v \in AV_{v,n,n'}, t \in T_v \tag{2.3}$$

$$\begin{aligned}& GW_{g,n,t} + \sum_{v,n'} GX_{g,v,n',n,t-(Atime_{v,n',n})+1} + Gdelta_{g,n,t} \\ & \quad = GW_{g,n,t+1} + \sum_{v,n'} GX_{g,v,n,n',t+1} \quad \forall g,n,t \mid t \ne |T|\end{aligned} \tag{2.4}$$

$$\begin{aligned}& VW_{v,n,t} + \sum_{n'} VX_{v,n',n,t-(Atime_{v,n',n})+1} + Vdelta_{v,n,t} \\ & \quad = VW_{v,n,t+1} + \sum_{n'} VX_{v,n,n',t+1} \quad \forall v,n,t \mid t \ne |T|, t \in T_v\end{aligned} \tag{2.5}$$

$$GW_{g,Gdestination_g,t} + GU_{g,t} = Gsize_g \quad \forall g,t \mid t \in TA_g \tag{2.6}$$

$$\sum_{v\in V^H} VW_{v,n,t} \le NlandingZones_n \quad \forall n,t \tag{2.7}$$

$$\sum_{\substack{v \in V^W \\ n' \in N}} VX_{v,n,n',t} + VX_{v,n',n,t-(Atime_{v,n',n})+1} \leq NdockSpaces_n \quad \forall n,t \tag{2.8}$$

$$VW_{v,n,t+1} \geq \sum_{\substack{n' \in AV_{v,n',n} \\ Atime_{v,n',n} \leq t}} VX_{v,n',n,t-(Atime_{v,n',n})+1} \quad \forall v \mid v \in V^H, n,t \mid t \neq |T|, t \in T_v \tag{2.9}$$

$$Gsize_g Together_{g,t} \leq GW_{g,Gorigin_g,t} \quad \forall g,t \in TE_g \tag{2.10}$$

$$GU_{g,t} = 0 \quad \forall g,t \mid t \geq GlatestArrival_g \tag{2.11}$$

$$GW_{g,n,Gavailable_g} = 0 \quad \forall g,n \tag{2.12}$$

$$GX_{g,v,n,n',Gavailable_g} = 0 \quad \forall g,n,n',v \mid v \in AV_{v,n,n'} \tag{2.13}$$

$$VW_{v,n,Vavailable_v} = 0 \quad \forall v,n \tag{2.14}$$

$$VX_{v,n,n',Vavailable_v} = 0 \quad \forall v,n,n' \mid n' \in AV_{v,n,n'} \tag{2.15}$$

GX, GW, and *GU* variables are non-negative and integer (2.16)

VX, VW, VS, and *Together* variables are non-negative and binary (2.17)

6. Description of the Formulation

The objective function (2.1) minimizes 'cost' in the sense described in Section C.

Constraint (2.2) enforces vehicle capacity, while constraint (2.3) enforces the application of a fixed cost for vehicle utilization if the subject vehicle makes any trips.

Constraint (2.4) and (2.5) enforce balance of flow for personnel and vehicles through nodes.

Constraint (2.6) accounts for personnel who have not arrived at their destination as unmet demand, for the purposes of applying penalties and ensuring eventual arrival.

Constraint (2.7) limits the number of helicopters at a node to the number of helicopter landing spots at that node, while constraint (2.8) limits the number of watercraft that can arrive at or depart from a node in a single time period to the number of embarkation/debarkation spots.

Constraint (2.9) prevents a helicopter from leaving a node during the first period following its arrival, thus accounting for the time required to load, unload, and refuel the helicopter.

Constraint (2.10) requires that for a group to be considered intact, for the purposes of eligibility for the *delay departure incentive*, the number of personnel in the group remaining at their originating node must equal the group size.

Constraints (2.11) – (2.15) are 'boundary' conditions for the problem. In particular, (2.11) enforces requirement for all personnel to reach their destination by the latest acceptable arrival time. Constraints (2.12) – (2.15) prevent personnel and vehicles from traveling during the time period in which they are instantiated in the problem. Note: this constraint is necessary because the aforementioned balance of flow constraints rely on the prior time period to constrain the current period, thus leaving the first period for each entity in the problem unconstrained (allowing the model to instantiate phantom people and vehicles if left unchecked). To make this constraint transparent to the user, the user defined start time for the problem and initial availability times are decremented by one time period in the model's implementation. As a result, a problem defined by the user to begin at 06:00h with five minute time periods and with groups and vehicles also becoming available at 06:00 will actually begin at 05:55 in the implementation, allowing scheduled movement to begin at 06:00.

Constraints (2.16) and (2.17) limit the range of all decision variables to non-negative and integer or binary values.

E. IMPLEMENTATION

The mixed-integer T-AH HAT optimization model described in Section D has been implemented in Xpress-MP [Dash Optimization, 2008], on a 2GHz personal

desktop computer with 2Mb of RAM. Xpress-MP tackles the problem by first solving a relaxed, linear version using the dual simplex algorithm, then utilizes a branch and bound technique to search for optimal integer solutions [Dash Optimization, 2007]. All of our scenarios (described in Chapter III) are solved within at least 5% of optimality in no more than one hour of computational time (often, in only a few minutes).

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III. COMPUTATIONAL RESULTS AND ANALYSIS

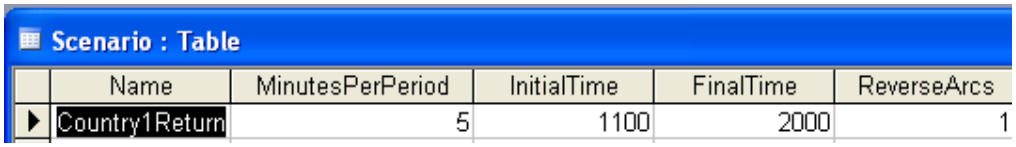
This chapter provides quantative analysis of the efficiencies gained by using the T-AH HAT optimization model compared to manual scheduling. To frame and carry out this analysis, parameter inputs to the model are discussed, criteria for evaluating SSTP solutions are defined, and SSTP scenarios are introduced. Chapter III also uses T-AH HAT to perform analysis of potential modifications to the T-AH class of ship.

A. USER-DEFINED PARAMETERS

1. Scenario Parameters

User selection of the problem's start time, end time, and minutes per period goes to the heart of balancing problem complexity with tractability. Smaller increments of time provide greater model resolution and reduce unwanted delay caused by conservatively rounding up travel times. Unfortunately, the cost of small time increments comes in the form of additional decision variables and constraints in the model; time is component of six different decision variable arrays, one of them five dimensional ($GX_{g,v,n,n',t}$), so the effects of time increment size and length of planning horizon on problem complexity is significant. Faced with this complexity, it is possible a planner would choose to optimize a half day's transportation schedule, vice the fully operational day in a single run. These half-day schedules are suitable to the problem because daily personnel movement can be broken down into two distinct phases, the movement of personnel from the T-AH out to the mission sites in the morning (outgoing phase), and then return of T-AH personnel from mission sites in the evening (returning phase). Modeling over a shorter span of time allows for greater resolution in the individual time periods while maintaining an acceptable model run-time. Of course, some transportation for patients, personnel and visitors may need to be scheduled midday, and this is accommodated in the model.

User scenario input is illustrated in Figure 7. Significantly, while the user sets the span of the model's time periods in terms of minutes per period, adjustments are made in the implementation to ensure the relative relationship between time period based model features are not distorted.



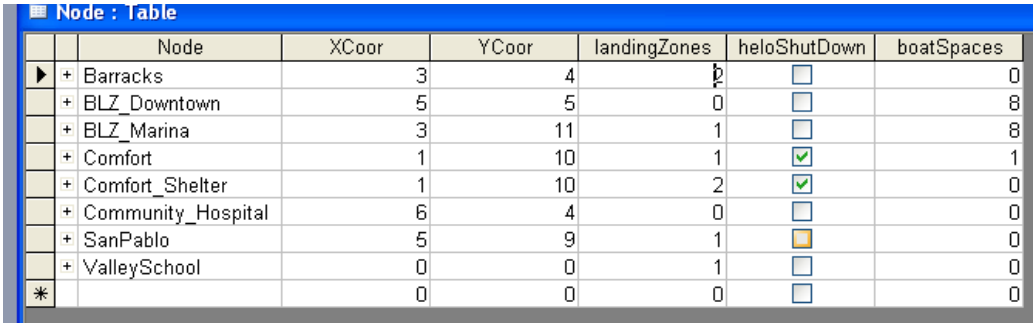
Scenario : Table

	Name	MinutesPerPeriod	InitialTime	FinalTime	ReverseArcs
▶	Country1Return	5	1100	2000	1

Figure 7. User-defined scenario parameters

2. Nodes

In addition to assigning names to each node, the user also defines several node characteristics: the number of landing zones at the node, whether or not an embarked helicopter can shutdown at the node, and the number of docking spaces where watercraft can simultaneously load and unload passengers. Although the T-AH helicopter shelter will typically be assigned two landing zones, this does not literally mean a helicopter can land in the shelter; the only path to shelter should be from the T-AH flight deck, and so the shelter's landing zones simply represent the ability to store helicopters. Figure 8 depicts this user interface. Note: assignment of spatial X and Y coordinates to each node, as shown below, allows for creation of a network map, although this feature has not been pursued in this thesis.



Node : Table

		Node	XCoor	YCoor	landingZones	heloShutDown	boatSpaces
▶	+	Barracks	3	4	2	☐	0
	+	BLZ_Downtown	5	5	0	☐	8
	+	BLZ_Marina	3	11	1	☐	8
	+	Comfort	1	10	1	☑	1
	+	Comfort_Shelter	1	10	2	☑	0
	+	Community_Hospital	6	4	0	☐	0
	+	SanPablo	5	9	1	☐	0
	+	ValleySchool	0	0	1	☐	0
*			0	0	0	☐	0

Figure 8. User-defined node parameters

3. Topography

The user must define the connectivity between the nodes within the modeled network. A value of zero in the node-to-node travel time for any transportation asset indicates the path between those nodes is infeasible for that vehicle type. A positive value represents the time, in minutes, required for the specified vehicle type to transit between the specified nodes. Two categories of watercraft have been established, fast boat and slow boat, to reflect the variation in speed likely to be seen between watercraft of different design. Figure 9 depicts this user interface. It is noted that while the model makes no specific allows for sea state and its affect on watercraft travel time, the user may take sea state into account when defining (or redefining based on changing weather conditions) the relevant node-to-node travel times.

Arc : Table

NodeFrom	NodeTo	Helicopter	BusVan	FastBoat	SlowBoat
BLZ_Downtown	Barracks	0	20	0	0
Comfort	Barracks	15	0	0	0
Comfort	BLZ_Downtown	0	0	30	60
BLZ_Marina	BLZ_Downtown	0	10	20	40
Comfort	BLZ_Marina	10	0	40	80
Comfort	Comfort_Shelter	15	0	0	0
BLZ_Downtown	Community_Hospital	0	10	0	0
BLZ_Marina	Community_Hospital	0	15	0	0
Comfort	SanPablo	30	0	0	0
Comfort	ValleySchool	35	0	0	0
BLZ_Marina	ValleySchool	30	120	0	0

Figure 9. User-defined topography parameters

4. Personnel

The user represents personnel in the model by defining groups, and can assign unique parameters to each of them. Group parameters, depicted in Figure 10, have been previously discussed (see Chapter II, Section C for details).

GroupPax : Table

Code	Size	Origin	Destination	Available	DesiredArrival	LatePenalty	LatestArrival	MoveIncent	DelayDepart
MTF_1	20	SanPablo	Comfort	1600	1800	15	2000	1	20
MTF_2	55	Barracks	Comfort	1600	1800	15	2000	1	3
MTF_3	25	Community_Hospital	Comfort	1600	1800	15	2000	10	0
MTF_4	45	ValleySchool	Comfort	1530	1800	15	2000	1	3
Patients_A	14	BLZ_Marina	Comfort	1330	1500	10	2000	1	0
Patients_B	12	Barracks	Comfort	1300	1600	10	2000	1	0
Seabees	18	ValleySchool	Comfort	1500	1800	15	2000	1	3

Figure 10. User-defined personnel parameters

5. Transportation Assets

The user must enumerate all transportation assets in the problem. As depicted in Figure 11, for each asset, the user must provide a unique name, node of origin, initial time available, asset type (helicopter, ground vehicle, or watercraft), capacity, fixed cost for utilization, and period cost for utilization.

TranspAsset : Table

Code	Origin	Available	Helicopter	BusVan	FastBoat	SlowBoat	Capacity	FixedCost	PeriodCost
BOAT_1	BLZ_Marina	1100	☐	☐	☐	☑	30	0	1
BOAT_2	BLZ_Marina	1100	☐	☐	☐	☑	30	0	1
BUS_1	ValleySchool	1100	☐	☑	☐	☐	45	0	1
HN1_1	BLZ_Downtown	1100	☐	☐	☑	☐	40	30	2
HN1_2	BLZ_Marina	1100	☐	☐	☑	☐	70	30	2
MH60_1	Comfort	1100	☑	☐	☐	☐	10	300	40
MH60_2	Comfort_Shelter	1100	☑	☐	☐	☐	10	300	40
VAN_1	BLZ_Downtown	1100	☐	☑	☐	☐	15	0	1
VAN_2	BLZ_Downtown	1100	☐	☑	☐	☐	15	0	1
VAN_3	BLZ_Marina	1100	☐	☑	☐	☐	15	0	1
VAN_4	BLZ_Marina	1100	☐	☑	☐	☐	15	0	1
VAN_5	BLZ_Marina	1100	☐	☑	☐	☐	15	0	1
	Comfort	1	☐	☐	☐	☐			10

Figure 11. User-defined transportation asset parameters

At a minimum, the *period cost* for each vehicle should be set to one. A vehicle with a period cost of zero is likely to 'wander' in the optimized schedule because, without some cost associated with movement, a schedule where the un-penalized vehicle makes nonsensical trips without passengers is just as good (just as optimal) as a similar schedule without the 'wandering'.

The "FixedCost" parameter shown as a column in the Figure 11 screenshot corresponds to $VfixedCost_v$ defined in the model formulation, and should be used sparingly. A fixed cost other than zero applied to a single vehicle v generates additional active constraints numbering on the order of n^2t (one for each instance of the decision variable $VX_{v,n,n',t}$ for that v). as well as creating an additional binary decision variable

VS_v. To illustrate the effect of this added complexity, a problem instance that solves to optimality in 82 seconds with no active fixed cost constraints takes 167 seconds to solve with two active fixed cost constraints, and 2,334 seconds with four active fixed cost constraints. As a rule, the planner should avoid using the fixed cost constraints for transportation assets unless they are specifically trying to limit the number of assets used during the day, or conducting analysis on the number of vehicles required to achieve acceptable schedules (perhaps in advance of making decision regarding the number of host nation vehicles to rent). The fixed cost should not be considered interchangeable with the variable cost.

B. CRITERIA FOR SCHEDULE EVALUATION

Many criteria can be defined for evaluating a proposed transportation schedule as it relates to the SSTP. Such criteria may be used to compare one feasible solution to another. The criteria which follow have been selected to evaluate how well a schedule performs in the key areas of supporting mission site operations ashore, minimizing transportation and waiting time for personnel, and making efficient use of transportation assets. We assume mission site operations criteria are of primary concern because overall mission performance can be equated to, and is critically constrained by, hours of ashore mission site operation, where the amount of HA conducted is a function of the number of hours ashore mission sites are manned (fully or partially). We also introduce the term *wait time* in the context of personnel criteria, as explained below. The list of criteria in each category follows.

Mission Site Operations Criteria:

- For how long will each mission site be fully manned during the day?
- For how long will each mission site be partially manned during the day?

Personnel Criteria:

- What is the average transit time for personnel by group and overall?

- What is the average time between the first and last personnel departure in each group, or, in other words, for how long are personnel waiting to begin transportation after their group becomes mission-ineffective because it has been broken up by the start of transport? This will hereafter be referred to as *wait time*.

Transportation Utilization Criteria:

- For how long was each asset in use?
- What was the overall ratio of seat utilization to capacity for each transportation type and overall?

C. GENERIC OPERATIONAL TOPOGRAPHY SCENARIOS

Three generic operational topography scenarios have been created to represent typical situations faced by the T-AH during a HA visit to a host nation where the T-AH has remained at sea. These scenarios will be used to evaluate model performance (Section E below), as well as to conduct sensitivity analysis relating to changes in transportation asset availability or operational parameters (Section F below). These three scenarios (hereafter referred to as Scenario 1, Scenario 2, and Scenario 3, respectively) are loosely based on visits to Belize, Colombia, and Guatemala observed by the author and other NPS personnel during COMFORT's 2007 deployment. All scenarios share some common parameters: two embarked helicopters, two slow organic watercraft on the T-AH, and problems initiating at 06:00h and continuing until 20:00h with 10-minute time periods. Although the T-AH HAT model is capable of scheduling many groups of personnel throughout the day (e.g., patients, VIP visitors to the ship, or supplemental medical personnel sent ashore) only the core group of personnel traveling to the mission sites (MS) is included in these scenarios because the mid-day movement is generally less constrained and thus less interesting to our analysis. MSs discussed in connection with each of these scenarios are indexed MS1, MS2, and so forth according to the number of MSs represented in the scenario. To convey how these three scenarios represent a range of nuanced variations in the operational situation, a short description of each follows, with other varying parameters shown in Table 1:

Scenario 1. The general situation is the T-AH is anchored in a position offshore such that there are 80-minute and 70-minute travel times by slow watercraft from T-AH to the two active BLZs, respectively. Four mission sites are in operation. One site, one of two that are relatively remote, has been accessed to have the greatest medical need. Priority is given to maximizing mission site operation at the high-need site through (a) a relatively large *expedite arrival penalty* for the outgoing trip from the T-AH, and (b) a relatively large *delay departure incentive* for the return trip.

Scenario 2. The general situation is the T-AH is anchored in a position offshore such that there is are 90-minute and 60-minute travel times by slow watercraft from ship to the two active BLZs, respectively. Four mission sites are in operation. In addition to the T-AH's embarked helicopters, the host nation has also provided two helicopters that must be scheduled. One site, a hospital, does not open its doors until 09:00h, so there is no utility in an early arrival; however, the hospital will remain open in the afternoon so long as T-AH personnel are available to see patients. This is reflected in the database by applying a *delay departure incentive* to the group supporting the hospital both when scheduling their outgoing trip (to maximize their rest on the T-AH and avoid an unnecessarily early arrival) and when scheduling their return (to maximize operating hours ashore).

Scenario 3. The general situation is the T-AH is anchored in a position offshore such that there is a 90-minute travel time by slow watercraft from ship to either of two active BLZs. Three missions sites are in operation, one co-located with one of the BLZs (no ground transport required), and two others inland. One of the mission sites is a hospital with fixed operating hours, so there is no utility in arriving at the site earlier than the desired arrival time, and likewise there is no utility in staying beyond the designated return time. This is reflected in the database by applying a *delay departure incentive* to the group supporting this location when scheduling their outgoing trip (to maximize their rest on the T-AH and avoid an unnecessarily early arrival) while using an *expedite arrival penalty* to expedite their return trip. At the other two mission sites, operational hours are not restricted by anything other than the transportation schedule, so in both cases the

associated groups of personnel are defined with *expedite arrival penalties* for their outgoing trips and *delay departure incentives* for their returns.

Table 1. Three generic operational topography scenarios

	Scenario 1	Scenario 2	Scenario 3
# Ashore Mission Sites	5	4	4
# Transshipment Sites	2	1	1
# Personnel Ashore	170	130	178
# Host Nation Ground Vehicles	6	5	2
# Host Nation Watercraft	2	2	3
# Host Nation Helicopters	0	2	0

D. APPLICATION OF MONTHLY FLIGHT HOUR CONSTRAINT

A significant constraint on the availability of embarked helicopters to SSTP solutions comes from a monthly limitation on the gross number of flight hours utilized (previously discussed in Chapter II, Section C). We now address the problem of applying this monthly constraint over a set of daily SSTPs. This discussion precedes further analysis because the ability to control the number of flight hours used in a T-AH HAT optimization will be important in allowing comparisons between optimized and manual schedules where similar levels of helicopter utilization between solutions allow for a more meaningful (apples to apples, in parlance) comparison.

We have explored various techniques to allocate helicopter flight hours among daily transportation problems. Among them, the most promising uses an iterative process where the objective function penalty associated with helicopter utilization per period of time ($Vperiodcost_v$) is first set to an equal level across a set of daily problems. Then iterative adjustments are made to the penalty until aggregate helicopter utilization among all problems reaches the desired level. This iterative technique is also effective in controlling helicopter utilization in a single SSTP. It is noted that helicopter flight hours

could have been controlled in individual problems through a constraint rather than manipulation of objective function penalties, but this would not have provided a means of determining what the appropriate constraint should be if dealing with an aggregate (monthly) allowance and multiple SSTPs where the marginal value of flight hours differs among SSTPs.

The benefit of flight hour allocation across a set of SSTPs by this process is demonstrated in Section E of this chapter following analysis where manual and optimized schedules are compared with flight hours matched at the individual SSTP level (vice in the aggregate).

E. COMPARISON OF MANUAL AND AUTOMATED SCHEDULING

1. Generation of Pseudo-Manual Schedules

It is desirable in any analysis of an optimization tool to determine how much better the optimized solution is compared to what is available without the benefit of optimization. Ideally, we would compare actual, manually produced transportation schedules from a prior T-AH HA operation with an optimized schedule produced by our model implementation in order to quantify the improvement realized through optimization. Unfortunately, we do not have detailed data reflecting actual, manually generated schedules to use for comparison purposes. We do, however, have a good understanding of the manual transportation scheduling process as detailed in Chapter I, Section B.3. This allows us to develop an algorithm to generate pseudo-manual schedules by generously approximating those that would be created manually. Steps of the pseudo-manual schedule algorithm are:

1) Muster all MTF personnel at the time of the earliest morning departure, regardless of when actual departure will occur.

2) Execute movement of all personnel traveling by watercraft to BLZs prior to beginning ground transportation from corresponding BLZs to mission sites.

3) Apportion ground transportation among the groups of personnel on a pro-rata basis, or if vehicles are not obviously subdividable among groups, then by assigning the remainder vehicles to the largest groups.

4) Once assigned to a group, use a vehicle exclusively to support that group by moving personnel from the BLZ to the group's mission site by the most direct route.

5) Use helicopters exclusively to effect movement of the group associated with the most distant mission site from the T-AH subject to group size being less than 40. Do not use helicopters for any other purpose.

6) Conclude operations at mission sites and commence ground transportation for return to BLZ at a time which allows each group to return to the BLZ one hour before group's desired arrival time at the T-AH.

7) Wait until personnel from all groups have reached the BLZ before beginning transportation to the T-AH by watercraft. Do not stage watercraft at the BLZ (unless that is their native starting position) in advance of personnel arriving there.

An algorithm adhering to the above outline has been implemented and used to generate schedules corresponding to the three generic scenarios described in Section C. In the manually generated schedules, we find a total of 24 hours and 40 minutes of helicopter flight time is utilized (totaled from one instance of each scenario).

2. Comparison of Individual Pseudo-Manual and Optimized Schedules

Optimized schedules are produced utilizing the T-AH HAT model implementation for the three scenarios. In order to match the flight hours used in the optimal schedules to those used in the manually generated schedules, the iterative method of helicopter variable cost adjustment is utilized, in this case to reach a like amount of helicopter utilization in the optimized schedule comparable to the corresponding manual schedule. That is, we iterate helicopter costs for each individual scenario, independent of the other scenarios. In the next section we will find and apply a single helicopter cost across all three scenarios that, in aggregate across all scenarios, leads to the same amount of total utilization corresponding to the manual schedules.

For Scenario 1, a T-AH HAT optimized schedule is generated with 5 hours and 10 minutes of helicopter flight time, appropriate for comparison to the corresponding pseudo-manual schedule that used 5 hours and 20 minutes correspondingly. A comparison across many relevant criteria of the Scenario 1 pseudo-manual and optimized schedules is shown in Table 2. We see the duration of fully manned operations at MS1 is reduced in the optimized schedule; this is because the pseudo-manual algorithm assigns helicopters to exclusively support this particular MS. At the other three MSs, and overall, the duration of fully manned operations increases by 5 hours and 30 minutes (19% increase). Although there is a decrease, in terms of percentage, in the number of partially manned hours, these hours are not as significant as the fully manned hours. The 9% improvement in total (fully and partially manned) hours is actually conservative because the partially manned hours are treated with proportionate weight in this statistic. MS4, which is given priority by the planner as described in Section C, enjoys a 31% improvement in fully manned time. Regarding average personnel travel times, we again find that while performance decreases for MS1 in the optimized schedule, it is improved at all other MSs and overall.

Table 2. Scenario 1 Pseudo-Manual and T-AH HAT Optimized Results Comparison. Significant results in bold font. Durations expressed in hours:minutes format.

	Pseudo-Manual	T-AH HAT Optimized	% Change From Manual (Parenthesis Indicate Undesirable Change)
Helicopter Per-Period Cost	N/A	100	N/A
Duration MS1 Fully Manned	9:50	7:00	(29%)
Duration MS2 Fully Manned	5:20	7:10	34%
Duration MS3 Fully Manned	5:00	8:50	77%
Duration MS4 Fully Manned	4:20	5:40	31%
Duration MS5 Fully Manned	4:20	5:40	31%
Combined Hours Fully Manned	**28:50**	**34:20**	**19%**
Combined Hours Partially Manned	5:10	2:40	(48%)

	Pseudo-Manual	T-AH HAT Optimized	% Change From Manual (Parenthesis Indicate Undesirable Change)
Combined Hours Full and Partially Manned	**34:00**	**37:00**	**9%**
Group 1 Average Travel Time	1:00	3:10	(217%)
Group 2 Average Travel Time	4:51	2:19	52%
Group 3 Average Travel Time	5:00	1:49	64%
Group 4 Average Travel Time	6:20	5:16	17%
Group 5 Average Travel Time	7:50	6:10	21%
Combined Average Travel Time	**5:08**	**3:31**	**31%**
Combined Average Wait Time	0:22	0:22	-
Helicopter Flight Time	**5:20**	**5:10**	**3%**
Average Transportation Asset Seat Utilization Rate	57%	45%	(19%)

Results of the Scenario 2 comparison are shown in Table 3. Notable in the Scenario 2 results is that the helicopter flight time in the optimized schedule cannot be matched to the 8 hours and 40 minutes consumed in the manual schedule by adjusting per-period penalty costs ($(VperiodCost_v)$. Even with the per-period penalty set to 1.00 for embarked helicopters (a level ensuring this cost will be dwarfed by other components of the objective function, but still sufficient to prevent vehicle wandering), the T-AH HAT optimization needs not to utilize more than 6 hours of helicopter flight time. This indicates utilization of helicopters in the pseudo-manual schedule was gratuitously suboptimal. As a consequence, the overall improvements seen, a 6% increase in fully manned MS hours and a 34% decrease in average personnel travel time, were achieved while simultaneously reducing helicopter flight hours by 31%. The ability to avoid wasting flight hours of little of no marginal value in one problem will prove to be beneficial when we later consider reallocation of flight hours between problems.

Table 3. Scenario 2 Pseudo-Manual and T-AH HAT Optimized Results Comparison. Significant results in bold font. Durations expressed in hours:minutes format.

	Pseudo-Manual	T-AH HAT Optimized	% Change From Manual (Parenthesis Indicate Undesirable Change)
Helicopter Per-Period Cost	N/A	1	N/A
Duration MS1 Fully Manned	8:40	9:00	4%
Duration MS2 Fully Manned	6:30	7:50	21%
Duration MS3 Fully Manned	6:30	7:30	15%
Duration MS4 Fully Manned	9:00	8:10	(9%)
Combined Hours Fully Manned	**30:40**	**32:30**	**6%**
Combined Hours Partially Manned	0:20	2:40	700%
Combined Hours Full and Partially Manned	**31:00**	**35:10**	**13%**
Group 1 Average Travel Time	1:25	1:52	(32%)
Group 2 Average Travel Time	3:10	1:48	43%
Group 3 Average Travel Time	3:10	1:26	55%
Group 4 Average Travel Time	4:30	2:00	56%
Combined Average Travel Time	**2:41**	**1:47**	**34%**
Combined Average Wait Time	0:16	0:18	(18%)
Helicopter Flight Time	**8:40**	**6:00**	**31%**
Average Transportation Asset Seat Utilization Rate	46%	60%	30%

For Scenario 3, the most significant improvement occurs in the category of average personnel travel time, which decreases by 11% in our optimized schedules. Notably, the fully manned time at MS1, where the scenario indicates priority should be given to maximizing operating hours and is prioritized accordingly in the T-AH HAT objective function, realizes an 11% increase in fully manned hours (compared to only a

1% increase overall among MSs). This may be an indication of the effectiveness of the model in prioritizing the movement of personnel bound for a particular MS, although we must recognize the dynamics of each particular scenario are also likely to have much influence over where optimization realizes its largest gains.

Table 4. Scenario 3 Pseudo-Manual and T-AH HAT Optimized Results Comparison. Significant results in bold font. Durations expressed in hours:minutes format.

	Pseudo-Manual	T-AH HAT Optimized	% Change From Manual (Parenthesis Indicate Undesirable Change)
Helicopter Per-Period Cost	N/A	110	N/A
Duration MS1 Fully Manned	4:30	5:00	11%
Duration MS2 Fully Manned	8:40	8:30	(2%)
Duration MS3 Fully Manned	6:40	8:00	20%
Duration MS4 Fully Manned	5:50	4:30	(23%)
Combined Hours Fully Manned	**25:40**	**26:00**	**1%**
Combined Hours Partially Manned	4:20	7:30	73%
Combined Hours Full and Partially Manned	**30:00**	**33:30**	**12%**
Group 1 Average Travel Time	5:41	3:05	46%
Group 2 Average Travel Time	1:50	2:06	(15%)
Group 3 Average Travel Time	3:40	2:25	34%
Group 4 Average Travel Time	1:20	4:03	(204%)
Combined Average Travel Time	**3:12**	**2:50**	**11%**
Combined Average Wait Time	0:25	0:31	(24%)
Helicopter Flight Time	**10:40**	**10:40**	**0%**
Average Transportation Asset Seat Utilization Rate	48%	42%	(13%)

3. Comparison of Pseudo-Manual and Optimized Schedules

In the previous section, the benefit of a T-AH HAT optimized schedule was shown in three scenarios where in each case, the optimized schedule took advantage of a quantity of helicopter flight hours equal or nearly equal to what was used in the corresponding, manual schedule. In this section, we find and apply a single helicopter marginal utilization cost ($VperiodCost_v$) across all three scenarios that, in aggregate, lead to the same amount of total utilization corresponding to the manual schedules, but with a different distribution of hours among the optimized scenarios. This is intended to demonstrate the marginal benefit of helicopter flight hours is not the same in every scenario, and an efficient allocation of flight hours should not be pro-rata nor allocated on the basis of exclusively supporting a single mission site (as is called for by the pseudo-manual algorithm).

Runs of T-AH HAT conducted to support the previous section, and some additional runs conducted as we iterate towards the desired amount of total utilization, yield a table of helicopter utilization penalties and associated quantity of flight hours shown in Table 5. Complicating matters is the inelasticity of helicopter utilization to penalties in cases where the helicopter provides the only feasible or only realistic means to a mission site.

From these, we see in Table 5 that a $VperiodCost_v$ of 40, applied to helicopters across all three problems, leads to the same amount of helicopter utilization, in aggregate, as was employed in the manual schedules. Comparing the $VperiodCost_v$ of 40 optimized schedules with the original optimized schedules ($VperiodCost_v$ of 100, 1, and 110 respectively) we find additional performance improvements as depicted in Table 6. This demonstrates that the utility of allocating flight hours among daily problems by this algorithm, instead of on a pro-rata or other arbitrary basis, is that flight hours are assigned based on where they will have the greatest impact in improving aggregate objective function value across the set of individual problems.

Table 5. Helicopter utilization penalties and the associated quantity of flight hours, for three scenarios, iteratively explored in order to match aggregate flight hours across the scenarios' optimized schedules to the aggregate flight hours derived from the pseudo-manual scheduling process. Durations expressed in hours:minutes format.

	Flying Hours			
$VperiodCost_v$ for embarked helicopters	Scenario 1	Scenario 2	Scenario 3	Total
Pseudo-Manual Schedule	5:20	8:40	10:40	24:40
$VperiodCost_v = 1$		**6:00**		
$VperiodCost_v = 40$	***8:10***	***4:20***	***12:00***	***24:30***
$VperiodCost_v = 80$	6:10		12:00	
$VperiodCost_v = 100$	**5:10**		11:40	
$VperiodCost_v = 110$			**10:40**	
$VperiodCost_v = 120$	3:40	3:40	8:20	15:40

Table 6. Comparison of (1) pseudo-manual schedules, (2) T-AH HAT optimized schedules without reallocation of helicopter flight hours, and (3) T-AH HAT optimized schedules with flight hour reallocation among three scenarios. Durations expressed in hours:minutes format.

	(1) Pseudo-Manual	(2) Optimized Without Reallocation	(3) Optimized With Reallocation	(4) % improvement from (2) to (3)	(5) % improvement from (1) to (3)
All Scenarios Total Combined Hours Fully Manned	85:10	92:50	95:20	3%	12%
All Scenarios Average Travel Time	3:40	2:43	2:34	5%	26%

F. ANALYSIS OF POTENTIAL T-AH MODIFICATIONS' IMPACT ON MISSION PERFORMANCE

The T-AH is an imperfect platform for Naval HA for reasons stated in Chapter I (although it should be noted there is no perfect platform for operations as dynamic as HA). Nonetheless, it is the primary platform available for large-scale naval medical operations, and will likely remain so in the coming years. For this reason, it is important to consider modifications to the platform that could mitigate its flaws when conducting HA. Two potential modifications, both real and near-term possibilities, are the addition of a second flight deck landing spot and the addition of two 150-passenger patient tender watercraft. To assess the impact of these potential modifications on mission performance, the primary criterion of hours of ashore mission site operation will be used.

1. Analysis: T-AH Certified to Use Two Helicopter Landing Spots

The effect of having two vice one helicopter landing spots on the T-AH has been explored by relaxing constraint (2.7) regarding flight deck landing spots. This relaxation allows up to two helicopters to be active on the flight deck at any given time. We assume a helicopter shelter still exists, although scheduling a helicopter to move from flight deck to shelter may now be driven by the optimized schedule only if more than two helicopters are involved in the scenario.

A comparison is conducted over three scenarios of optimized schedules with and without the addition of a second landing spot. For each comparison, the utilization of helicopter flight hours is made nearly equal between the with and without second landing spot optimized schedules (21 hours and 21 hours and 50 minutes, respectively) by the iterative technique so a like comparison can be made. We find that the combined (all mission sites) hours of fully manned operations increase by 4% with the addition of a second landing spot, despite utilizing slightly fewer aggregate flight hours (see Table 7).

Relating this improvement to the general allocation of flight hours, we calculate (without any statistical certainty due to the small sample size) a rough estimate of the ratio of additional operating hours ashore to flight hours utilized by adding a second landing spot is 4 (additional operating hours) / 21 (flight hours) = 0.19. That is, a

decision maker evaluating the prospect of adding a second landing spot might consider the benefit in terms of the number of flight hours of operation expected in a given deployment, and then use this ratio to estimate, for example, that a deployment consuming 400 flight hours would gain an additional $0.19 \times 400 = 76$ hours of ashore mission site operations if a second landing spot were added.

Table 7. Comparison of optimized schedules with and without the addition of a second helicopter landing spot. Durations expressed in hours:minutes format.

	Current T-AH	T-AH With Two Landing Spots	% Improvement
All Scenarios Helicopter Flight Time	**21:50**	**21:00**	**4%**
All Scenarios Total Combined Hours Fully Manned	**92:50**	**96:50**	**4%**

2. Analysis: T-AH Modified to Carry Two Patient Tender Watercraft

The effect of adding two patient tender watercraft to the T-AH, deployable by a boat davit system, has been explored by adding representations of such vehicles to the scenarios introduced earlier in the chapter, and by relaxing constraint (2.8) regarding watercraft docking to reflect the boat davits' capability to launch and recover watercraft. We assume the boat davits may be operated independently, and do not interfere with the docking of other watercraft alongside the T-AH in the current fashion. Besides relaxing constraint (2.8), it is also noted that boat davit deployable watercraft would address an issue, not represented in our model, with safely embarking and debarking patients and personnel from the T-AH in conditions when having them leap from a watercraft into the T-AH's loading bay (the current practice) becomes harrowing.

In Table 8, we see a comparison over three scenarios of optimized schedules with and without the addition of patient tender watercraft. For each comparison, the utilization of helicopter flight hours has been made nearly equal between the with and without patient tender watercraft optimized schedules by the iterative technique. We find

that the combined (all mission sites) hours of fully manned operation increase by 10% with the addition of two patient tender watercraft. Simultaneously, helicopter utilization decreases by 10% in this comparison, and by comparing Table 7 and Table 8 results, we see that the addition of patient tender watercraft leads, in this case, to a dramatic 40% reduction in helicopter utilization compared to optimized schedules where helicopters necessarily played a larger role in problem solution.

Table 8. Comparison of optimized schedules with and without the addition of patient tender watercraft, over three scenarios. Durations expressed in hours:minutes format.

	Current T-AH	T-AH With Two Patient Tender Watercraft	% Improvement
All Scenarios Helicopter Flight Time	**14:20**	**12:40**	**10%**
All Scenarios Total Combined Hours Fully Manned	**90:40**	**99:40**	**10%**

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IV. CONCLUSION AND FUTURE RESEARCH

A. CONCLUSION

This thesis demonstrates the application of mathematical optimization to T-AH HA operations. By addressing the Transportation Problem (one of many defined problems associated with T-AH HA), we show how the efficiency of HA operations may be increased.

Even small increases in efficiency must be viewed against the scale of a T-AH HA deployment; USNS COMFORT treated nearly 95,000 patients over the course of four months in 2007. Optimal transportation schedules guided by the T-AH HAT model, regardless of the case-specific percentage of improvement, can translate into thousands more patients treated (or lives saved in a DR mission). By extension, these additional patients treated (or other HA provided if the service is non-medical) equate to additional mission accomplishment, as we are able to further the favorable impression of the U.S. conveyed by HA. In particular, our optimized schedules improve average duration of ashore mission site operations by between 9% and 13% in three scenarios, compared to a set of pseudo-manually generated schedules.

We have also used T-AH HAT to quantify the benefit of potential modifications to the T-AH class. Analysis conducted with three sample scenarios has demonstrated that certification of a second flight deck landing spot on the T-AH may yield a 4% increase in ashore mission site fully manned operational time, while the addition of two patient tender watercraft may yield a 10% increase (over already optimized schedules in both cases).

The U.S. Navy currently has at least one T-AH HA deployment scheduled per year through 2012. Additional deployments are possible, particularly in response to natural disaster. This means that the Navy's institutional experience in T-AH HA will more than double in the next five years. In support of this new core capability for U.S.

Naval forces, it is necessary and appropriate that robust analysis efforts complement the gain in practical operational experience as HA capabilities mature.

B. DEPLOYMENT OF THE OPTIMIZATION TOOL

USNS MERCY is expected to commence an HA deployment in the summer of 2008. Destroyer Squadron (DESRON) 31, based in Pearl Harbor, has been selected to command the mission. This thesis will be distributed to DESRON 31 upon completion for consideration of fielding an implementation of the T-AH HAT model in conjunction with their deployment. A preliminary description of T-AH HAT has already been circulated among parties responsible for planning the MERCY deployment, including the U.S. Pacific Fleet (PACFLT) and personnel aboard the hospital ship itself.

Challenges to deploying an implementation of T-AH HAT are twofold. First, a license for the proprietary software owned by *Dash Optimization*, the developer of Xpress-MP, would need to be arranged. It is assumed the implementation of T-AH HAT would reside on a stand-alone laptop rather than the T-AH's network. Second, some amount of training would have to be conducted with the planning officer responsible for the SSTP. While an in-depth understanding of mathematical optimization would not be required of this individual, he or she would need to become comfortable with the conception of minimizing cost in the objective function. Because this individual is already faced with the practical constraints modeled in T-AH HAT, and has the same objectives as those in the model's objective function, he or she will already have an intuitive understanding of the model and should be able to make successful use of it after a brief period of familiarization. Familiarization could be facilitated by NPS personnel in person (ideally) or remotely.

C. DISSEMINATION OF ANALYSIS

An overview of this thesis work has also been shared with key individuals responsible for the T-AH class. A personal briefing was delivered by the researcher to Mr. J. Kaskin, the Director, Strategic Mobility & Combat Logistics Division, Office of the Chief of Naval Operations (N-42). Mr. Kaskin has responsibility for all Military

Sealift Command ships, which includes both MERCY and COMFORT. This thesis work has also been informed by discussions with Mr. J. Zarkowsky, the Director for Future Deployable Platforms at the Bureau of Medicine and Surgery (BUMED), who will be on distribution for this thesis in hopes that he may, in turn, be informed by the results and analysis in the context of decisions regarding potential future utilization of, and modifications to, the T-AH class.

D. RELATED TOPICS FOR FURTHER RESEARCH

Among the many other compelling T-AH HA Operations Research topics not addressed by thesis, several deserve particular emphasis for future research. In the course of briefing this thesis to Mr. J. Kaskin, N-42 on the Navy Staff, interest in a comparative analysis of naval HA performed by a T-AH versus an amphibious assault ship was expressed. Interestingly, the amphibious assault ship USS PELILEU conducted an HA mission in the Pacific during 2007, providing a case in point for comparison with T-AH HA. It is tempting to assume ship-to-shore transportation constraints would not be a factor when utilizing a ship designed to move people quickly ashore from her flight deck and well deck, but this is not necessarily the case. Because preparing the ship to launch or recover a landing craft from her well deck is a complex process, PELILEU generally only made use of her landing craft for one round trip per day, moving a single large wave of people out in the morning and back in the evening. The prospect of waves of helicopters flying from PELILEU's large flight deck is enticing, however, only two MH-53 helicopters were embarked during most of the mission. These were found by some to be insufficiently flexible and reliable to affect the scheduled and emergent movement of personnel and patients between ship and shore during the day. Even if ship-to-shore transportation became un-constraining to an amphibious assault ship engaged in HA, other important criteria for comparison would be the T-AH's non-combatant status, differences in the number of operating rooms and overall medical capacity, cost, and opportunity cost of committing either platform to HA at the expense of their availability to operate elsewhere and in other capacities.

Two other compelling operational topics are the concept of operations for the ashore mission sites (which are dynamic, unique, and involve queuing and optimization issues) and definition and inventory management of a customized allowance list of pharmaceuticals appropriate to T-AH HA. Interest in these topics has been expressed by COMFORT medical operations department personnel and Bureau of Medicine and Surgery personnel, respectively. An opportunity to observe ashore mission site operations would be critical to anyone developing the first topic. Some familiarity with pharmaceutical allowances, or a partnership with an individual or organization with such familiarity, would be necessary for the second topic.

At the strategic level of HA mission planning, critical planning decisions involving the selection of countries as HA recipients and duration of T-AH stay in each operating area could be informed by Operations Research analysis. Analysis in this area could leverage past research into naval mission planning and scheduling, taking into account criteria unique to HA. Also compelling would be a modeling of the personnel assignment process that draws specialized medical personnel from their parent commands to the T-AH for an HA deployment, with consideration of the possibly unique mix of skills required aboard a T-AH optimally manned to conduct HA.

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